

# SOIL SCIENCE

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## MINNESOTA GLACIAL SOIL STUDIES: I. A COMPARISON OF SOILS ON THE LATE WISCONSIN AND IOWAN DRIFTS<sup>1</sup>

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### INTRODUCTION

About 99 per cent of the surface of Minnesota was traversed by one or more ice sheets during the glacial period and practically all its soils have been formed upon the resulting mantle of glacial drift, and the aeolian and lacustral deposits derived from this. Three of the ice invasions, coming from the northeast, left reddish-colored deposits, while the others, from the northwest, left gray drift. Where the soils have been developed directly upon the glacial mantle the question arises as to what relation, if any, exists between their composition and the age and source of the drift upon which they are found.

The drift from the earliest invasion from the northwest—the Nebraskan—appears to have been everywhere buried or obliterated by the later glaciations. The latest, known in Minnesota as the Young Gray Drift, covers the greater portion of the state, and is flanked on the southeast and southwest by a margin of Old Gray Drift intermediate in age. The ice sheets that deposited these radiated from centers northwest of Winnipeg and in their advance to the southward brought a great quantity of calcareous debris, consisting of boulders, cobblestones, gravel, and rock-flour derived from the Paleozoic limestones west and south of Lake Winnipeg. As the composition of the till of these drifts when first laid down appears to have been very similar, any marked differences found in the character of the soils formed upon them may be associated with differences in their relative ages.

In such an investigation it does not suffice simply that the soils chosen for study should have developed upon drift sheets originally similar in character while differing greatly in age. It is highly important that they should have had similar surface drainage conditions, have been of similar texture, have been exposed to a similar climate and have borne a similar vegetation. Lastly, they should be as nearly virgin as possible. In Rice County (fig. 1), in which Young Gray Drift occupies the west side and Old Gray Drift the east, these conditions could be complied with. On both sides of the dividing line the rolling lands were covered by deciduous forest and the more level areas by prairie.

<sup>1</sup> Published with the approval of the Director as Paper No. 227, of the Journal Series of the Minnesota Agricultural Experiment Station.

## SOIL AND SOIL-FORMING AGENCIES

The depth of the superficial layer that is included under the general designation "soil" varies from writer to writer, some considering it to extend only as deep as plant roots penetrate while others insist on including the full depth to which the parent rock has been affected by percolating water. In southeastern Minnesota the crops derive their mineral nutrients and their water supply chiefly from the first 3 feet of soil, and with the possible exception of alfalfa, almost exclusively from within the first 5 feet. Hence, while in agronomic questions pertaining only to that part of the state we scarcely need consider the portion below the fifth foot, the whole of the first 3 feet is to be regarded as well within the root zone.

The surface of a till plain or a terminal moraine, that has just been exposed by the recession of an ice sheet, is to be regarded not as *soil*, but as the parent rock upon which soils may be developed through the agency of percolating waters, carrying carbon dioxide and soluble salts, combined with that of living organisms and the organic compounds formed upon their death. The form of alteration induced in the parent rock by these agencies will depend upon the vegetative covering, temperature, precipitation, rate of evaporation, and level of the ground-water, as well as upon both the perviousness of the parent rock to descending water and the water-retaining capacity of its superficial portion. The character of the vegetative covering, in its turn, will be determined in part by the climate and in part by the character of the parent rock, or of the soil developed upon this. Accordingly, the character of a soil will depend upon both the properties of its parent rock and the climate where it has been formed. Older soils generally are more dependent upon the climate than upon the parent rock. Thus a granite, a wind-laid silt loam, and a lacustral clay may weather to produce soils of very similar character, when all three have been exposed for a sufficient length of time to the same climate, while they will give rise to soils of entirely different character under other climatic conditions.

## DRIFT SHEETS EXPOSED IN MINNESOTA

Ten or twelve successive stages are generally recognized in the Pleistocene, or Glacial Period, in North America. Some of the ice sheets radiated from Keewatin centers north or northwest of Minnesota, and others from Labradorian centers east of James Bay. Each invasion, with the possible exception of the last, appears to have been separated from its immediate predecessor by an interglacial interval during which a milder climate prevailed, drainage channels were formed, vegetation flourished on the freshly exposed drift and soils were developed. Each succeeding ice sheet planed off most of the surface over which it advanced, cutting down the elevations, filling most of the valleys, and burying the earlier deposits under a fresh mantle of glacial debris. Drift from the earlier glaciations was more or less incorporated into

the mass of fresh material carried by the advancing ice. On most of the traversed areas the soil was thus removed but here and there tracts escaping the general abrasion were buried by the new drift. When now exposed in cuts the old soils on these furnish part of the evidence of interglacial intervals.

The generally accepted classification of the Pleistocene (1, p. 56; 6, p. 383) in the interior of North America is as follows:

- 6a. Recent epoch—Glacio-lacustrine and Champlain substages.
6. Later Wisconsin, the sixth advance. In Minnesota includes the Young Gray Drift, the Young Red Drift of the Superior Lobe and the Patrician Readvance.
- 5a. Fifth interglacial interval, as yet unnamed. The interval may have been too brief to permit of leaching and soil formation.
5. Earlier Wisconsin, the fifth invasion. In Minnesota the Young Red Drift or Patrician.
- 4a. Fourth interglacial interval—Peorian.
4. Iowan, the fourth invasion. Glacial geologists are not entirely agreed as to the separate identity of this, and in Minnesota the Iowan has been mapped along with the Kansan as Old Gray Drift.
- 3a. Third interglacial interval—Sangamon.
3. Illinoian, the third invasion. In Minnesota represented by a small area of Old Red Drift.
- 2a. Second interglacial interval—Buchanan or Yarmouth.
2. Kansan, the second invasion. In Minnesota known as the Old Gray Drift and exposed in southeastern and southwestern counties.
- 1a. First known interglacial interval—Aftonian.
1. Nebraskan, Pre-Kansan, or Jerseyan, the first invasion.

The earlier stages of glaciation appear to have been much longer than the later and some of the interglacial intervals probably much exceeded the time which has elapsed since the disappearance of the last ice sheet.

All the above-mentioned glacial invasions crossed what are now the borders of Minnesota. The first, or Nebraskan, radiating from the Keewatin field, covered the greater part of the state, extending far beyond its southern boundary. The drift from this has been completely mantled by later deposits and no natural exposure is known in Minnesota, it being encountered only in deep wells and in an occasional railroad cut or excavation.

The second, or Kansan, also from a Keewatin center, appears to have covered every part of the state except the extreme southeastern corner—the Minnesota portion of the Driftless Area, which is more extensively represented in the neighboring portions of Wisconsin and Iowa. Part of the mantle left by this ice sheet is exposed as Old Gray Drift in two southwestern and in several southeastern counties, a narrow belt lying between loess-covered Kansan on the one side and Late Wisconsin or Iowan on the other.

The third, or Illinoian, coming from the northeast, barely entered the state to the east and southeast of St. Paul, leaving the deposit known as the Old Red Drift.

The fourth, or Iowan, has been a subject of controversy since it was first described by the late Dr. Calvin of the Iowa Geological Survey. The divergent views are indicated in the next section.

The next invasion, the Early or Earlier Wisconsin, from the northeast, covered a considerable area to the west and southwest of Lake Superior (fig. 1), leaving the Young Red Drift, which extends to some little distance south

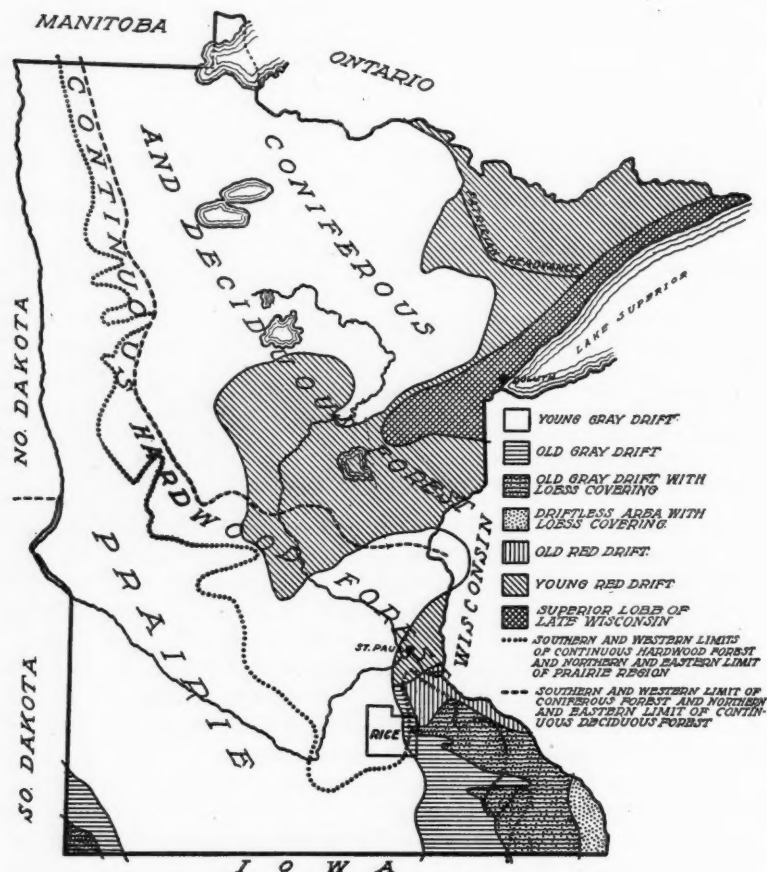


FIG. 1. MAP OF MINNESOTA SHOWING LOCATION OF THE AREA STUDIED (RICE COUNTY), AND ITS RELATION TO THE DIFFERENT GLACIATIONS AND THE NATURAL VEGETATION

After glacial map of Leverett and Sardeson (11) and vegetation map of Rosendahl and Butters (13, p. 111).

of St. Paul, even into the northern edge of Rice County. Part of the drift from this was covered by that of the next glaciation.

In the last invasion, the Late Wisconsin, there appear to have been three simultaneous advances of the ice, each from a different center. The most

extensive radiated from a Keewatin center to the northwest of Minnesota, covering a much larger portion of the state than any of its predecessors following the Kansan. The mantle left by it, and known as the Young Gray Drift, overlies most of the older drift from the northwest. In contrast with the Old Gray Drift the younger formation is characterized by numerous lakes, marshes and swamps. Fully developed drainage lines are found only where these were formed by the torrential streams which prevailed as the front of the last ice sheet was receding. The main body of the ice advanced far into Iowa and its deposit is referred to as the Des Moines Lobe (fig. 2), while an offshoot, spreading northeastward from north of St. Paul to a little beyond the

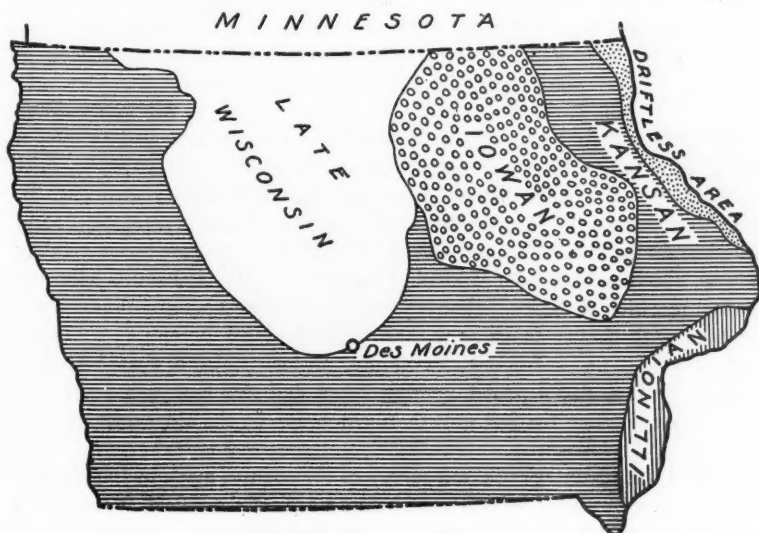


FIG. 2. GLACIAL MAP OF IOWA

After Alden and Leighton (1)

Wisconsin line, is known as the Grantsburg Lobe. In addition to these two lobes, which together constitute the Young Gray Drift of Minnesota, there was a contemporaneous Superior lobe, in which the ice advanced southwestward along the bed of Lake Superior, spread out to the north, west and southwest and left a red till. At the same time there appears to have been a readvance of ice from the north, and Leverett refers to this, in a private communication, as the Patrician Readvance.

The older drifts have been exposed to a much longer leaching than their place in the above tabulation might suggest. Using as a time unit the period that has elapsed since the Late Wisconsin drift was first exposed to erosion, and "a collation of the judgment of five of the glacial geologists who have most

studied the data in their most favorable expressions," Chamberlin and Salisbury (6, p. 413-414) report the following estimates of the relative ages:

	<i>time units</i>
From the Late Wisconsin to the present. . . . .	1
From the Early Wisconsin to the present. . . . .	2 to 2½
From the Iowan to the present. . . . .	3 to 5
From the Illinoian to the present. . . . .	7 to 9
From the Kansan to the present. . . . .	15 to 17
From the Nebraskan to the present. . . . .	x

The Nebraskan, although clearly much older than the Kansan, is everywhere buried by later deposits, thus preventing the application of estimates based upon erosion.

#### ADVANTAGES OFFERED BY RICE COUNTY

For such a study as that here reported Rice County appeared to offer a better opportunity than any other area in the state. The youngest drift occupies part of it while the rest is covered by an older gray drift (fig. 3). Both were deposited by ice sheets radiating from the same general center and bringing similar calcareous and clayey material from the northwest. Lying side by side they have been exposed to the same climatic influences following the last recession of the ice. Prairie as well as forest occurs naturally on both. On land with similar topography, and with the same vegetative covering, we were able to find soils similar in texture. A long period of time, including at least one interglacial period, in which floras and soils had been developed, had elapsed between the first growth of vegetation on the older drift and the exposure of the younger.

We had the advantage of a soil survey of the county, made in 1909 by the United States Bureau of Soils (4), and before we selected our fields for sampling in the fall of 1914 Mr. Frank Leverett, of the United States Geological Survey, who was just completing a detailed study of the glacial history of the state, kindly accompanied one of us over the full length of the dividing line between the two drifts in the county.

At the time the soil survey was made the existence of two drifts in the county was recognized (4, p. 21-23), Leverett having personally indicated the boundary to the surveyors, but in the report no attempt was made to differentiate soil types on the basis of difference in age of the drift, although it is stated that "the limestone from which much of this drift (Kansan) is derived, has long since given way to the agencies of weathering and only the more resistant rocks are left, whereas in the Wisconsin drift limestone and shales in addition to numerous cherty and crystalline rocks are very common" (4, p. 21).

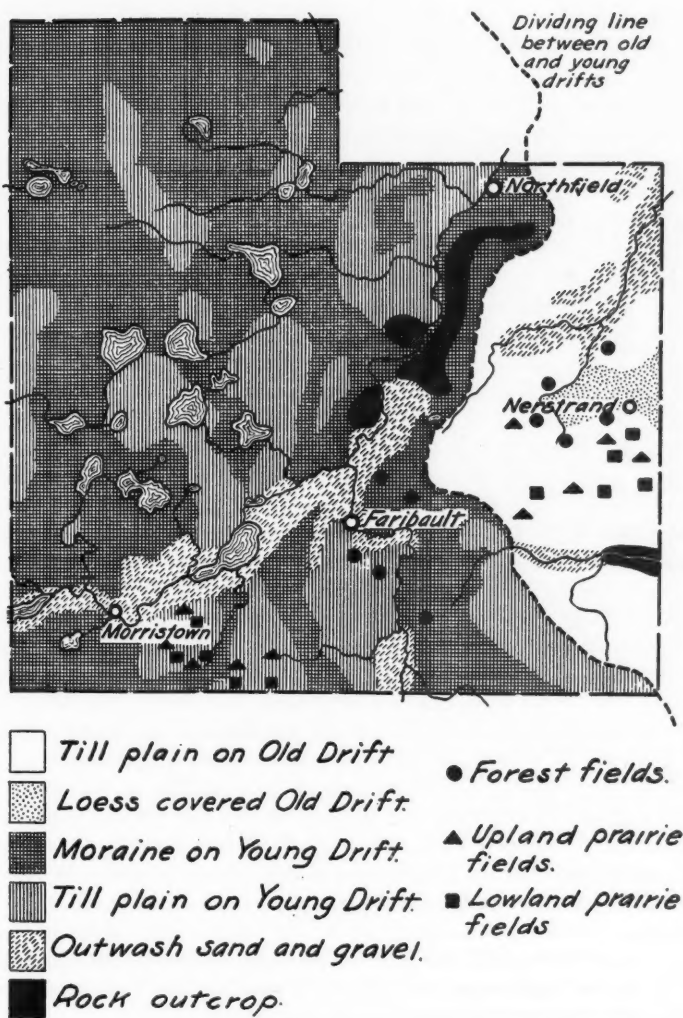


FIG. 3. MAP OF RICE COUNTY, SHOWING SURFACE FORMATIONS (AFTER LEVERETT AND SARDESON (11)) AND THE LOCATION OF THE THIRTY FIELDS SAMPLED

#### AGE OF THE TWO DRIFTS IN RICE COUNTY

Glacial geologists are agreed as to the general outlines of the eastern side of the Des Moines lobe, and hence as to the age of the younger drift in Rice County, and also as to the drift which extends eastward from the Des Moines lobe to the Driftless Area being much older, but they are not agreed upon the

age of the latter, as to whether it is Kansan, Illinoian, or Iowan, or partly one and partly another. Some consider it as of post-Illinoian but pre-Wisconsin age, and hence as Iowan, while others are not satisfied that it may not be either Kansan or Illinoian. On a recent map of the Iowa Geological Survey (1, pl. 14) the older drift in northeastern Iowa is shown as chiefly Iowan, with a fringe of Kansan, while an equally recent map of the Minnesota Geological Survey (11) indicates only one older drift exposed in southeastern Minnesota (fig. 1 and 2).

The question of the age of the older drift, and hence its identification, is very important. If it is Kansan with the surface exposed since Kansan time, and its soils are similar in composition to those on the nearby Late Wisconsin, it would appear useless to seek for characteristic differences by comparisons of soils on any other two drifts originally similar in composition, unless they had been exposed to climatic conditions more conducive to leaching than those which have prevailed in Rice County. On the other hand, the lack of evidence of leaching in the case of Iowan compared with Late Wisconsin, does not exclude a probability of a distinct difference between Late Wisconsin and Kansan, or even between Iowan and Kansan. This is well illustrated by Kay's explanation of the formation of "gumbotil" on the older drifts—Nebraskan, Kansan and Illinoian—as a product of long weathering and leaching, and its absence from the Iowan and Wisconsin as due to the relative youth of these (9).

About thirty years ago W. J. McGee showed that in northeastern Iowa, the part east of the Wisconsin moraine, there are two drift sheets differing greatly in age (12, p. 472 and p. 496). Later Calvin differentiated three distinct drift sheets as the Nebraskan, Kansan and Iowan. The existence of the last as distinct from the Kansan and Illinoian was questioned in a paper by Leverett (10, p. 280-283), to which Calvin replied with a summary of the evidence (5). Very recently the whole question has been reviewed by Alden and Leighton (1), who spent the summers of 1914 and 1915 on field investigations in northeastern Iowa. They conclude that there is a post-Kansan drift sheet older than the Illinoian and younger than the Wisconsin, and that there is warrant for the continued use of the Iowan as one of the major subdivisions of the Pleistocene classification. The drift of the Kansan and Iowan is so similar lithologically that the boundary line between the two has had to be determined largely upon the basis of topography—where the smooth swale topography gives way to sharply dissected topography.

In the Iowan area, though it is not generally dissected by sharp-cut, eroded valleys, there are yet present nearly everywhere the main features of maturely branching stream-erosion systems. The valleys divide and subdivide in dendritic fashion, and their branches reach most parts of the area. . . . In the Kansan there is not only deep dissection but the ramifications of the branches are developed in minute detail down to ravines and gullies trenching the slopes at intervals of a few rods. Convex curves prevail on the slopes and more or less sharply cut, V-shaped, cross-profiles predominate except in the broader flat-bottomed valleys. . . . In the Iowan drift area . . . V-shaped cross-profiles are rarely seen. The side slopes are long and of low grade. . . . The minor valleys are thus broad open swales (1, p. 61-62).

In the Iowan they find a lesser depth of leaching of carbonate, only from 4 to 6 feet in general, measuring from the surface, compared with 12 to 15 on the Kansan, while the till also is oxidized to a lesser depth, 7 to 15 on the Iowan compared with 15 to 25 on the Kansan. The characteristic *ferretto* of the Kansan, a reddish brown or dark brown zone, 1 to 1.5 feet thick and consisting of a dense sticky clay, is absent from the Iowan. On the Kansan they found gumbotil covered by loess, by Iowan drift, or by both, but on the Iowan gumbotil is absent.

Leverett and Sardeson, referring to the southeastern part of Minnesota, and with Alden and Leighton's review of the Iowan question in mind, recognize an area in which the general depth of leaching is less and the surface not so deeply reddened by oxidation, and in which the valleys are in some cases mere swales and shallower than in the Kansan drift area in southern Iowan, but "because of the vagueness of the features the limits of the Iowan drift, or the extent of Iowan glaciation, are matters on which there is a wide difference of opinion. . . . There has been perhaps a slight removal of the leached and weathered surface of the Kansan drift in exposed locations and redeposition of this material in the valleys and depressions. The valleys of this problematical area often head in shallow draws or sloughs which are wet and ill drained, but the district is entirely free from lakes and inclosed basins such as abound in the later or Wisconsin drift region" (11, p. 49). As yet no attempt has been made to trace the eastern boundary of the Minnesota portion of this problematical area.

Our forest and upland prairie fields east of the boundary line have the mantled mature-erosion type of topography which Alden and Leighton consider characteristic of the Iowan, show no *ferretto*, and the depth to which leaching of carbonate has penetrated averages only between 4 and 5 feet from the surface. As the older drift where our samples were collected thus appears clearly to belong to what these authors describe as the Iowan, we may treat it as such without reference to the question of the retention of the Iowan as one of the major subdivisions of the Glacial Period.

#### SOIL TYPES

Fourteen soil types have been mapped in Rice County, but only three of the most extensive have representative areas on both sides of the boundary between the drifts, viz., (1) a forest-covered type (Carrington loam); (2) an upland prairie (Carrington silt loam); (3) a lowland prairie type (Fargo silt loam). These three were selected for our study.

The Carrington soils are derived from the weathering of the glacial drift. Carrington loam occupies the rolling uplands, the moraines in the case of the younger drift, is generally well drained and originally was nearly all covered with deciduous forest—part of what is known as the Big Woods. Winchell in his survey of the county made over 40 years ago (18, p. 652-654), mentions more than thirty species of trees, the most common ten, arranged in order of

frequency, being the following: basswood (*Tilia Americana*), white elm (*Ulmus Americana*), black oak (*Quercus velutina*), bur oak (*Quercus macrocarpa*), silver maple (*Acer saccharinum*), aspen (*Populus tremuloides*), sugar maple (*Acer saccharum*), slippery elm (*Ulmus fulva*), black ash (*Fraxinus nigra*), butternut (*Juglans cinerea*). The silt loam is found on the till plain and is confined to those higher lying portions of the county which were originally covered by prairie. Boulders, some very large, occur on both types. The Fargo slit loam, originally grassland, is a bottom-land type with a topography generally level, or with a very gentle slope toward a stream or bog, usually poorly drained and often with the water-table within 3 feet of the surface.

#### COLLECTION OF SAMPLES

##### *Selection of fields*

We collected samples from tracts that were still in as nearly virgin condition as it was possible to obtain. At the time the samples were collected, the fall of 1914, a few of the original settlers were still living and these were able to give much valuable information. Each site was selected only after the oldest settlers in the neighborhood had been consulted and a more or less complete history of it had been obtained. As an illustration of the value of such inquiries we might mention the case of an apparently natural grassland field occurring on silt loam soil. Living within a half-mile of the field was a very old gentleman who 56 years before had cleared the brush from it and every year since had seen the growth upon it.

The locations of the 30 sites finally selected are shown in figure 3, to all of which we will refer as "fields" although in the case of the upland prairie we did not find a single entire field that had never been plowed. In the case of this type, the most desirable of the three, the selection of satisfactory sites was a difficult task and finally all of the samples representing it were taken from along fence lines where the original sod had never been plowed so far as the oldest living settlers knew. In the case of the lowland prairie virgin fields were almost as difficult to find. On the Old Drift two rather poorly drained meadows provided two of the sites and both of these fields were plowed a few days after the samples were taken. Grassy roadsides were chosen for two others, and a line fence border for the fifth, while on the Young Drift all were from line fence borders or roadsides. The required number of satisfactory and properly distributed fields on the forest type were comparatively easy to locate. As both prairie types are so easily brought under the plow it is not surprising that fields in a virgin condition on them are now so rare.

In the case of each type on both drifts an effort was made to locate the five fields so that no two would be less than a mile apart and usually this was found possible. The general appearance of the fields on the three types is illustrated by plates 1, 2 and 3.

*Method of sampling*

Thirty fields were sampled, 15 on each of the two drifts, 5 on each of the three soil types. From each field four composite samples were prepared, these representing four successive levels of the first 3 feet, viz., 1-6, 7-12, 13-24, and 25-36 inches. Each is a composite of twenty individual samples taken with an auger, ten of which were from one part of the field and ten from another. The borings of each group of ten were in a straight line and approximately 10 yards apart. Two augers, one 2.0 and the other 1.5 inches in diameter, were used, the larger to take the surface section and to enlarge the hole preparatory to taking each of the lower sections with the smaller auger. We were careful to prevent the soil from the lower sections becoming contaminated with surface soil as the auger was being withdrawn. The composites made up from the twenty borings are referred to as the "field samples," while the "drift samples" from each type were prepared by combining equal weights of the five corresponding "field samples." Thus the drift samples are composites from 100 borings scattered over a considerable territory.

In the forest fields the surface coating of leaf-mold in nearly all cases had become so modified from allowing cattle to pasture in the woods that it was not considered representative of the original leaf-mold. Hence in taking the samples from this type the surface at each boring was freed of all leaves and woody fragments before the augers were used.

## TEXTURE

*Proportion of coarser particles*

As the samples were being taken all rock fragments less than 25 mm. in diameter brought up by the auger were included in the sample and wherever a fragment exceeding this size was encountered another boring was made a foot or so distant, the material from the first being rejected. In the case of all field samples we determined the coarser gravel, the portion included within the limits 2-25 mm. (table 1), and the average weight of its particles (table 2). More detail on this as well as on various other parts of the study has already been reported (15). On glacial areas such as these the proportion of material coarser than 25 mm. in diameter will vary considerably from place to place and its determination would involve the handling and separation in the field of large amounts of soil and subsoil.

On the forest type the average proportion of gravel in the four sections, or in the 20 samples, was much the same on both drifts, 2 per cent on the old and 1.83 per cent on the young, while the average weight of the particles was equally similar, viz., 0.030 and 0.026 gm., respectively. On both the maximum was found in the third foot. Although the variation from field to field on both is so great that we should not attach any great weight to the slight differences shown by the two drifts, it is worthy of note that the difference between the

TABLE 1  
Coarser gravel in the successive levels of the thirty fields

DEPTH	OLD DRIFT						YOUNG DRIFT					
	Field I	Field II	Field III	Field IV	Field V	Average	Field I	Field II	Field III	Field IV	Field V	Average
Forest												
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	0.93	0.33	0.53	0.03	2.03	0.77	0.47	1.07	0.64	1.79	0.46	0.89
7-12	1.02	0.31	0.63	0.13	0.03	0.42	0.94	0.75	0.27	1.65	0.26	0.77
13-24	2.52	1.28	1.93	0.19	0.02	1.19	1.52	1.70	1.10	4.25	0.18	1.75
25-36	6.22	6.48	8.24	0.04	0.08	4.21	1.81	2.93	2.90	4.92	1.98	2.91
Average 1-36*	3.23	2.69	3.58	0.10	0.38	2.00	1.34	1.85	1.48	3.63	0.94	1.83
Upland Prairie												
1-6	0.06	0.52	0.23	0.15	0.12	0.22	0.17	1.18	1.00	1.03	0.99	0.88
7-12	0.04	0.68	0.33	0.21	0.50	0.35	0.51	1.08	1.25	1.38	0.98	1.04
13-24	0.13	0.37	0.31	0.13	0.14	0.22	1.32	0.91	2.83	1.91	2.38	1.87
25-36	1.08	0.77	1.15	1.06	1.15	1.04	1.94	2.85	3.44	2.59	4.32	3.03
Average 1-36	0.42	0.58	0.55	0.46	0.53	0.51	1.20	1.63	2.46	1.90	2.56	1.95
Lowland Prairie												
1-6	0.00	0.35	0.00	0.00	0.00	0.07	0.67	0.23	0.64	0.58	0.46	0.52
7-12	0.00	0.17	0.00	0.70	0.07	0.19	1.00	0.23	1.06	1.44	0.83	0.91
13-24	0.00	0.16	0.20	0.27	0.36	0.20	0.94	0.79	1.51	4.28	0.68	1.64
25-36	0.36	2.21	0.17	0.85	0.82	0.88	1.65	1.06	2.07	4.38	1.57	2.15
Average 1-36	0.12	0.88	0.12	0.49	0.40	0.40	1.14	0.69	1.48	3.22	0.96	1.50

\* To secure the average for a 3-foot section the mean of the values for the two 6-inch sections is added to those for the second and third feet and the sum divided by three, a procedure followed in all tables reported in this article.

TABLE 2  
Average weight of particles of coarser gravel in the six groups of fields

DEPTH	FOREST		UPLAND PRAIRIE		LOWLAND PRAIRIE	
	Old-drift	Young drift	Old drift	Young drift	Old drift	Young drift
<i>inches</i>	<i>gm.</i>	<i>gm.</i>	<i>gm.</i>	<i>gm.</i>	<i>gm.</i>	<i>gm.</i>
1-6	0.022	0.029	0.025	0.039	0.002	0.022
7-12	0.024	0.020	0.035	0.026	0.019	0.020
13-24	0.032	0.025	0.021	0.024	0.053	0.026
25-36	0.035	0.028	0.033	0.024	0.046	0.023
Average 1-36	0.030	0.026	0.028	0.027	0.036	0.023

third foot and the overlying sections is generally more marked on the Old Drift, as though the disintegration of the original rock fragments had proceeded to a greater depth on this.

The topography of this type is the most rolling of any sampled and accordingly its surface soil is the most apt to be strongly eroded; hence it is not unlikely that much of the material originally at the surface on some of the fields has been carried away, bringing less weathered layers within the 3-foot section.

A mineralogical examination of the sand and gravel in the third foot-section on the two drifts showed that on the older considerably larger quantities of trap-rocks and iron minerals (limonite, magnetite) were present than on the younger while on the latter a higher percentage of quartz, light-colored quartzite, chert, and shales was observed, no trace of the last-named two rocks being found on the older.

On both the upland and the lowland prairie types the proportion of coarse gravel is appreciably higher on the younger drift, 1.95 compared with 0.51 per cent, and 1.50 with 0.40, respectively, as though the processes of weathering had advanced farther on the older. Less variation than on the forest type is shown from field to field. The average weight of the particles is alike on the upland prairie but on the lowland prairie it is the higher in the older drift. The differences between the averages for the two groups of lowland prairie fields is due chiefly to the large amounts of gravel found in field IV on the younger drift.

Thus on the whole the two drifts show no really characteristic differences in the proportion of coarse gravel in the 3-foot section, while the average weight of the particles is much the same from type to type and drift to drift.

#### *Moisture equivalents*

When a large number of samples are being compared in texture it is most convenient and often most satisfactory to use some single-valued expression directly related to the water-retaining capacity, either the hygroscopic coefficient or the moisture equivalent. In the present instance we determined the moisture equivalent of each sample, under our circumstances this being the more convenient of the two (tables 3 and 4). The values are shown graphically in figure 4.

The forest type shows the greatest variation from field to field as well as the coarsest texture, while the lowland prairie shows the finest texture and the greatest variation within the 3-foot section. In field IV of the latter type on the Old Drift the moisture equivalent of the surface section, 52.1, is practically twice that of the third foot, 25.9.

The averages for the five fields on the different types (table 4) show little variation from drift to drift. The lowland prairie appears to have a finer texture in the first foot on the older, but this is probably to be attributed to

its higher content of organic matter. This similarity in texture from drift to drift in the case of each of the three types still further enhances the desirability of the area and of these soil types for the chemical study reported in the following sections.

TABLE 3  
*Moisture equivalents of successive levels of the thirty fields*

DEPTH	OLD DRIFT						YOUNG DRIFT					
	Field I	Field II	Field III	Field IV	Field V	Average	Field I	Field II	Field III	Field IV	Field V	Average
Forest												
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	26.0	24.4	23.9	27.7	22.8	24.8	25.5	24.1	23.3	21.2	27.7	24.4
7-12	22.8	20.9	21.2	23.9	21.0	22.0	19.0	21.2	20.1	17.3	25.3	20.6
13-24	22.5	22.8	21.4	25.8	20.4	22.6	20.3	24.4	20.8	18.3	25.7	21.9
25-36	19.6	15.3	15.7	19.1	14.9	16.9	19.8	23.2	18.4	18.3	23.0	20.5
Average 1-36	22.2	20.2	19.9	23.6	19.1	21.0	20.8	23.4	20.3	18.6	25.1	21.6
Upland prairie												
1-6	33.3	27.3	32.9	28.7	31.1	30.6	35.3	28.5	26.2	28.8	29.1	29.6
7-12	31.7	27.9	32.1	28.0	30.7	30.1	35.0	24.3	24.2	28.3	26.9	27.7
13-24	28.6	27.3	29.5	26.3	28.8	28.1	33.3	21.6	22.5	26.7	24.5	25.7
25-36	23.8	24.7	25.9	22.5	23.7	24.1	34.3	22.1	23.1	26.4	23.4	25.9
Average 1-36	28.3	26.5	29.3	25.7	27.8	27.5	34.2	23.4	23.6	27.2	25.3	26.7
Lowland prairie												
1-6	44.7	45.5	40.9	52.1	46.5	45.9	40.5	34.5	35.3	34.1	35.1	35.9
7-12	37.8	38.2	36.7	36.8	36.6	37.2	36.8	27.3	37.5	32.2	32.3	32.8
13-24	29.9	29.9	31.9	30.0	28.6	30.1	35.6	26.6	35.6	26.9	26.7	30.3
25-36	24.3	24.5	27.5	25.9	23.3	25.1	35.1	27.8	32.5	26.3	26.0	29.5
Average 1-36	31.8	32.1	32.7	33.4	31.1	32.2	36.4	28.4	34.8	28.4	28.8	31.4

TABLE 4  
*Moisture equivalents of the six groups of fields*

DEPTH	FOREST		UPLAND PRAIRIE		LOWLAND PRAIRIE	
	Old drift	Young drift	Old drift	Young drift	Old drift	Young drift
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	24.8	24.4	30.6	29.6	45.9	35.9
7-12	22.0	20.6	30.1	27.7	37.2	32.8
13-24	22.6	21.9	28.1	25.7	30.1	30.3
25-26	16.9	20.5	24.1	25.9	25.1	29.5
Average 1-36	21.0	21.6	27.5	26.7	32.2	31.4

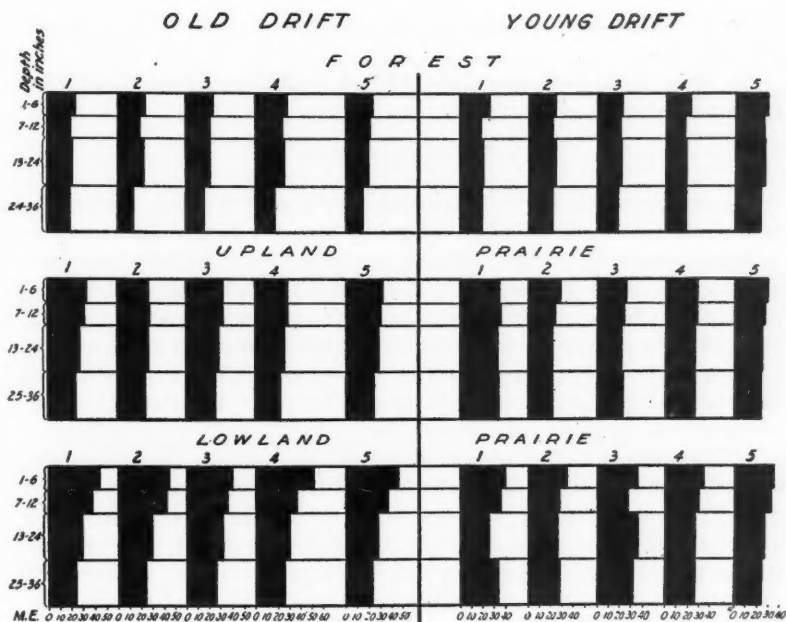


FIG. 4. DIAGRAM SHOWING MOISTURE EQUIVALENTS OF THE SOIL IN THE THIRTY FIELDS

## METHODS OF CHEMICAL ANALYSIS

In the case of each of the "drift samples," the composites from the group of five fields of a type on each drift, we made a complete or rock analysis and an organic-carbon determination. With the samples from the individual fields analysis was confined to nitrogen, carbon dioxide, and phosphoric acid, but the reaction and the color were determined, as well as the data reported in tables 1 and 3.

In the complete analysis we followed the methods in use in the laboratory of the United States Geological Survey (7) except in the case of the phosphoric acid for which the modification of the Washington method (17) developed by one of us (Rost) was employed (14).

Nitrogen was determined by the Gunning-Kjeldahl method and organic carbon by combustion with copper oxide in a current of oxygen, while for the reaction the Truog method (16) was used.

The volatile matter was determined by ignition to constant weight and hence includes the carbon dioxide.

The organic matter reported has been computed from the organic carbon— $C \times 1.724 = \text{organic matter}$ .

The water of constitution has been obtained by deducting the sum of the organic matter and carbon dioxide from the volatile matter.

The analytical data reported are the averages of concordant duplicate determinations.

For many of the analyses we are indebted to Mr. W. M. Shaw, formerly of this laboratory.

#### CHEMICAL COMPOSITION

The composition of the 24 drift samples is reported in tables 5, 6 and 7. In the later tables each individual constituent is dealt with separately in order to facilitate the study of the differences between the two drifts, the three types and the four successive levels. Further, in order to bring out as clearly as possible any effect that leaching may have had upon the original constituents other than the carbonates, we report the mineral constituents in tables 8 to 13 upon the basis of the carbonate-free, non-volatile portion of the soil, and not upon the oven-dried samples as in tables 5 to 7. For this reason the percentages in the latter tables must be distinguished from those in the former.

To illustrate our method of computation we may consider the silica in the surface 6-inch section and in the third foot of the lowland prairie on the old drift. The oven-dried samples were found to contain, respectively, 59.05 and 73.41 per cent of silica, 20.34 and 4.08 of volatile matter, and 0.30 and 0.84 of carbon dioxide. Assuming that all the carbon dioxide is present in the form of calcite, the corresponding percentages of this are 0.68 and 1.91. Thus the carbonate-free, non-volatile portion of the two samples constitutes 78.98 and 94.01 per cent of the oven-dried samples, and contains 74.76 and 78.09 per cent of silica. They thus show a difference of only 3.33 per cent compared with 14.36 shown by the ordinary statement of analysis in table 7.

#### *Silica*

This constituent is quite similarly distributed on the two drifts, and from type to type (table 8). The highest averages are for the forest and the lowest for the lowland prairie. There is no definite increase or decrease with increase in depth.

#### *Iron*

The iron is reported as ferric oxide in table 8-B. Although ferrous compounds were doubtless present no attempt was made to differentiate between ferrous and ferric iron, because of the large amount of organic matter in most of the samples and the interference of this with the determination of the proportion present in the ferrous condition.

All three types show a higher content on the older drift, the differences being least on the forest type. There is a steady increase with depth until the second foot is reached but this does not show any regular difference from the third.

TABLE 5  
Composition of forest type (Carrington loam)  
(Data for Young Drift in italics)

	1-6 INCHES	7-12 INCHES	13-24 INCHES	25-36 INCHES	AVERAGE 1-36 INCHES
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
SiO <sub>2</sub> .....	75.69 <i>76.34</i>	77.05 <i>77.37</i>	74.95 <i>76.26</i>	78.23 <i>76.98</i>	76.52 <i>76.70</i>
Al <sub>2</sub> O <sub>3</sub> .....	9.50 <i>9.52</i>	10.54 <i>10.66</i>	12.01 <i>11.81</i>	10.46 <i>11.77</i>	10.83 <i>11.22</i>
Fe <sub>2</sub> O <sub>3</sub> .....	2.93 <i>2.82</i>	3.41 <i>3.32</i>	4.23 <i>3.93</i>	4.04 <i>3.96</i>	3.81 <i>3.65</i>
MgO.....	0.70 <i>0.60</i>	0.71 <i>0.67</i>	0.94 <i>0.84</i>	0.78 <i>0.85</i>	0.81 <i>0.77</i>
CaO.....	1.06 <i>1.09</i>	0.92 <i>0.97</i>	0.97 <i>0.95</i>	1.02 <i>1.07</i>	0.99 <i>1.02</i>
Na <sub>2</sub> O.....	1.46 <i>1.41</i>	1.42 <i>1.42</i>	1.38 <i>1.40</i>	1.41 <i>1.42</i>	1.41 <i>1.41</i>
K <sub>2</sub> O.....	1.72 <i>1.86</i>	1.76 <i>1.99</i>	1.82 <i>1.96</i>	1.65 <i>1.76</i>	1.74 <i>1.88</i>
TiO <sub>2</sub> .....	0.68 <i>0.60</i>	0.73 <i>0.60</i>	0.69 <i>0.58</i>	0.60 <i>0.58</i>	0.67 <i>0.59</i>
P <sub>2</sub> O <sub>5</sub> .....	0.23 <i>0.19</i>	0.18 <i>0.15</i>	0.18 <i>0.14</i>	0.15 <i>0.14</i>	0.18 <i>0.15</i>
CO <sub>2</sub> .....	0.09 <i>0.10</i>	0.04 <i>0.06</i>	0.03 <i>0.05</i>	0.04 <i>0.04</i>	0.06 <i>0.06</i>
Organic C.....	2.83 <i>3.06</i>	1.34 <i>1.46</i>	0.79 <i>0.81</i>	0.50 <i>0.50</i>	1.12 <i>1.19</i>
Organic matter.....	4.87 <i>5.18</i>	2.31 <i>2.52</i>	1.36 <i>1.40</i>	0.86 <i>0.86</i>	1.94 <i>2.04</i>
Water of constitution.....	1.47 <i>1.45</i>	1.37 <i>1.57</i>	1.91 <i>2.33</i>	1.75 <i>1.98</i>	1.69 <i>1.94</i>
N.....	0.24 <i>0.26</i>	0.12 <i>0.12</i>	0.07 <i>0.08</i>	0.04 <i>0.04</i>	0.10 <i>0.10</i>
Volatile matter.....	6.41 <i>6.71</i>	3.73 <i>4.15</i>	3.32 <i>3.77</i>	2.66 <i>2.89</i>	3.68 <i>4.03</i>

TABLE 6  
*Composition of upland prairie type (Carrington silt loam)*  
 (Data for Young Drift in italics)

	1-6 INCHES	7-12 INCHES	13-24 INCHES	25-36 INCHES	AVERAGE 1-36 INCHES
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
SiO <sub>2</sub> .....	69.59 <i>72.89</i>	71.02 <i>73.62</i>	72.45 <i>75.24</i>	75.14 <i>73.65</i>	72.63 <i>74.05</i>
Al <sub>2</sub> O <sub>3</sub> .....	11.09 <i>10.46</i>	11.35 <i>10.87</i>	11.96 <i>11.35</i>	11.89 <i>12.13</i>	11.69 <i>11.38</i>
Fe <sub>2</sub> O <sub>3</sub> .....	3.55 <i>2.99</i>	3.81 <i>3.21</i>	4.40 <i>3.42</i>	4.78 <i>3.81</i>	4.29 <i>3.44</i>
MgO.....	0.81 <i>0.72</i>	0.84 <i>0.74</i>	0.85 <i>0.88</i>	0.93 <i>1.21</i>	0.87 <i>0.94</i>
CaO.....	1.13 <i>1.24</i>	1.14 <i>1.18</i>	1.02 <i>1.24</i>	0.93 <i>2.08</i>	1.03 <i>1.51</i>
Na <sub>2</sub> O.....	1.26 <i>1.39</i>	1.36 <i>1.35</i>	1.37 <i>1.33</i>	1.29 <i>1.31</i>	1.32 <i>1.33</i>
K <sub>2</sub> O.....	1.76 <i>1.66</i>	1.84 <i>1.74</i>	1.90 <i>1.86</i>	1.87 <i>1.87</i>	1.86 <i>1.80</i>
TiO <sub>2</sub> .....	0.64 <i>0.50</i>	0.64 <i>0.52</i>	0.64 <i>0.54</i>	0.70 <i>0.53</i>	0.66 <i>0.53</i>
P <sub>2</sub> O <sub>5</sub> .....	0.23 <i>0.18</i>	0.20 <i>0.17</i>	0.15 <i>0.14</i>	0.13 <i>0.11</i>	0.16 <i>0.14</i>
CO <sub>2</sub> .....	0.08 <i>0.07</i>	0.09 <i>0.05</i>	0.06 <i>0.13</i>	0.03 <i>1.06</i>	0.06 <i>0.42</i>
Organic C.....	4.76 <i>4.48</i>	3.77 <i>3.19</i>	1.83 <i>1.78</i>	0.75 <i>0.77</i>	2.28 <i>2.13</i>
Organic matter.....	8.20 <i>7.72</i>	6.50 <i>5.50</i>	3.15 <i>3.07</i>	1.29 <i>1.33</i>	3.93 <i>3.67</i>
Water of constitution.....	2.34 <i>1.58</i>	2.00 <i>2.25</i>	2.86 <i>2.14</i>	2.41 <i>2.86</i>	2.46 <i>2.30</i>
N.....	0.38 <i>0.36</i>	0.29 <i>0.28</i>	0.17 <i>0.16</i>	0.06 <i>0.07</i>	0.19 <i>0.08</i>
Volatile matter.....	10.52 <i>9.38</i>	8.58 <i>7.80</i>	6.07 <i>5.34</i>	3.73 <i>5.25</i>	6.54 <i>6.39</i>

TABLE 7  
*Composition of lowland prairie type ( Fargo silt loam )*  
 (Data for young drift in italics )

	1-6 INCHES	7-12 INCHES	13-24 INCHES	25-36 INCHES	AVERAGE 1-36 INCHES
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
SiO <sub>2</sub> .....	{ 59.05 68.08	{ 65.81 70.42	{ 71.71 72.02	{ 73.41 71.97	{ 69.18 71.08
Al <sub>2</sub> O <sub>3</sub> .....	{ 10.29 10.18	{ 11.46 10.62	{ 12.43 11.57	{ 12.28 12.64	{ 11.86 11.50
Fe <sub>2</sub> O <sub>3</sub> .....	{ 3.37 3.21	{ 3.79 3.21	{ 4.21 3.68	{ 4.14 3.95	{ 3.98 3.61
MgO.....	{ 1.02 1.07	{ 1.06 1.08	{ 1.21 1.23	{ 1.49 1.51	{ 1.25 1.27
CaO.....	{ 2.34 1.97	{ 2.08 1.84	{ 1.55 1.86	{ 1.92 2.16	{ 1.89 1.97
Na <sub>2</sub> O.....	{ 1.31 1.18	{ 1.48 1.29	{ 1.45 1.27	{ 1.59 1.18	{ 1.48 1.23
K <sub>2</sub> O.....	{ 1.57 1.60	{ 1.64 1.68	{ 1.83 1.71	{ 1.86 1.75	{ 1.76 1.70
TiO <sub>2</sub> .....	{ 0.60 0.60	{ 0.66 0.60	{ 0.73 0.60	{ 0.72 0.60	{ 0.69 0.60
P <sub>2</sub> O <sub>5</sub> .....	{ 0.31 0.23	{ 0.24 0.18	{ 0.19 0.15	{ 0.18 0.11	{ 0.21 0.16
CO <sub>2</sub> .....	{ 0.30 0.49	{ 0.20 0.57	{ 0.06 0.54	{ 0.84 1.04	{ 0.38 0.70
Organic C.....	{ 9.47 5.71	{ 5.38 3.91	{ 1.66 2.10	{ 0.62 1.00	{ 3.23 2.64
Organic matter.....	{ 16.32 9.84	{ 9.27 6.74	{ 2.86 3.62	{ 1.07 1.72	{ 5.57 4.54
Water of constitution.....	{ 2.72 1.35	{ 2.66 2.30	{ 2.49 2.27	{ 1.17 1.36	{ 2.62 2.40
N.....	{ 0.79 0.44	{ 0.47 0.31	{ 0.15 0.15	{ 0.04 0.06	{ 0.27 0.19
Volatile matter.....	{ 20.34 11.68	{ 12.12 9.61	{ 5.41 6.43	{ 4.08 5.87	{ 8.57 7.31

TABLE 8  
*Silica, ferric oxide, alumina and titanium in the different sections*

DEPTH	FOREST		UPLAND PRAIRIE		LOWLAND PRAIRIE	
	Old drift	Young drift	Old drift	Young drift	Old drift	Young drift
A. Silica						
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	81.04	82.03	77.93	80.56	74.76	78.07
7-12	80.11	80.84	77.84	79.95	75.28	79.03
13-24	77.58	79.34	77.24	79.73	75.92	77.98
25-36	80.45	79.34	78.10	77.93	78.09	78.42
Average 1-36	79.53	80.04	77.74	79.30	76.34	78.32
B. Ferric oxide						
1-6	3.14	3.03	3.97	3.30	4.26	3.68
7-12	3.55	3.46	4.17	3.48	4.33	3.60
13-24	4.38	4.09	4.69	3.62	4.46	3.98
25-36	4.15	4.08	4.97	4.03	4.40	4.30
Average 1-36	3.96	3.87	4.58	3.67	4.37	3.97
C. Alumina						
1-6	10.17	10.22	12.40	11.56	13.03	11.67
7-12	10.96	11.14	12.44	11.80	13.10	11.91
13-24	12.43	12.28	12.75	12.02	13.16	12.52
25-36	10.76	12.12	12.35	12.82	13.06	13.67
Average 1-36	11.25	11.70	12.51	12.17	13.09	12.66
D. Titanium oxide						
1-6	0.73	0.64	0.71	0.55	0.75	0.69
7-12	0.76	0.63	0.70	0.56	0.75	0.67
13-24	0.71	0.60	0.68	0.57	0.77	0.65
25-36	0.62	0.60	0.73	0.55	0.76	0.65
Average 1-36	0.69	0.61	0.71	0.56	0.75	0.66

#### *Alumina*

The alumina (table 8-C) is quite uniformly distributed on the two drifts as well as from type to type, although slightly higher in the prairie fields on the older drift, but on this it shows a minimum of 10.17 and a maximum of 13.16 per cent and on the younger a range from 10.22 to 13.67 per cent. As in the case of the ferric oxide, there is an increase with depth through the first three sections but the second foot is not distinctly higher than the third. The similarity in the alumina content on the two drifts is evident from the averages for the 3-foot sections of all three types, viz., 12.28 per cent on the older and 12.18 per cent on the younger.

*Titanium*

The titanium (table 8-D) although slightly higher on the older drift is very uniformly distributed, both from type to type and from the surface downward.

*Lime*

The total lime (table 9-A) in the different sections of the forest type is remarkably similar, the differences between the two drifts for any given level being no greater than that between duplicate determinations on the same sample. All calcium compounds at all readily soluble have evidently been

TABLE 9  
*Lime in the different sections*

DEPTH	FOREST		UPLAND PRAIRIE		LOWLAND PRAIRIE	
	Old drift	Young drift	Old drift	Young drift	Old drift	Young drift
A. Total lime						
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	1.13	1.17	1.26	1.37	2.96	2.26
7-12	0.96	1.01	1.25	1.28	2.37	2.06
13-24	1.00	0.99	1.09	1.31	1.64	2.01
25-36	1.05	1.10	0.97	2.20	2.02	2.33
Average 1-36	1.03	1.06	1.10	1.61	2.11	2.17
B. Lime in the form of carbonate as computed from CO <sub>2</sub> content						
1-6	0.09	0.10	0.10	0.10	0.40	0.65
7-12	0.07	0.08	0.10	0.07	0.25	0.69
13-24	0.07	0.05	0.07	0.16	0.08	0.68
25-36	0.06	0.07	0.04	1.36	1.06	1.33
Average 1-36	0.07	0.07	0.07	0.53	0.49	0.89
C. Lime in form of silicate (= A - B)						
1-6	1.04	1.07	1.16	1.27	2.56	1.61
7-12	0.89	0.93	1.15	1.21	2.12	1.37
13-24	0.93	0.94	1.02	1.15	1.56	1.33
25-36	0.99	1.03	0.93	0.84	0.96	1.00
Average 1-36	0.96	0.99	1.03	1.08	1.62	1.27

leached out of this type to a depth of more than 3 feet. On the upland prairie the amount in the first three sections is practically the same on both drifts, varying between 1.09 and 1.37 per cent. In the third foot, however, the quantity on the younger drift is more than twice as great, reaching 2.20 per cent, as compared with 0.97 on the older. On the lowland prairie there is no wide difference between the drifts, and the average for the three feet is 2.11 per cent in the case of the older and 2.17 in the younger.

The total lime in the surface section is generally slightly higher than in the second. It is withdrawn from the lower levels by plant roots, being largely deposited in the leaves and branches, on the death and decay of which it remains in the surface layer.

The amount of lime present as carbonate (table 9-B) has been computed from the carbon-dioxide content, assuming that all of this is present in the form of calcite. An appreciable quantity is shown on the upland prairie type only in the third foot-section of the Young Drift. A deficiency in this is shown in the second foot-section on the lowland prairie only on the Old Drift. With the forest type on both drifts the carbonate has been leached to a depth greater than 3 feet. On the older drift the two types, and on the younger the forest, have lost the more readily soluble calcium compounds to a depth of more than 3 feet. The upland prairie on the younger still retains a considerable amount in the third foot. Any serious leaching of the lowland prairie has been prevented by the poorly drained condition, as is well illustrated by table 9-B, which shows every section well supplied with carbonate except the second foot on the older drift.

Deducting the lime in the form of carbonate from the total gives the amount in the form of silicate (table 9-C), assuming that the quantity of gypsum is negligible. On each type the average amount is very similar on the two drifts except in the case of the lowland prairie, where it is slightly the higher on the older. On the prairie types from the surface downward, there is a general decrease in the amount of non-carbonate lime, while on the forest type there is but little variation.

The similarity in carbon-dioxide content from field to field is dealt with in a later section (tables 21 and 22).

### *Magnesia*

There is very little difference between the two drifts in the amount of magnesia (table 10) found on any of the types. As in the case of lime, the most occurs in the lowland prairie, the average being 1.35 per cent for the Old Drift and 1.39 on the Young. For the forest the averages are slightly lower than for upland prairie, being 0.84 per cent and 0.80 per cent, respectively for the two drifts. The magnesia content rises with increasing depth.

### *Ratio of lime to magnesia*

The ratio of total lime to magnesia (table 11-A) falls between 1.0 and 1.8, averaging 1.4 for the 3-foot section on all types. For each of these it is very similar on both drifts, the greatest difference being shown by the upland prairie, where, on the older drift, it is 1.2 as compared with 1.5 on the younger.

On both prairie types the ratio of non-carbonate lime to magnesia decreases from the surface downward (table 11-B), partly because of the similar decrease

in the non-carbonate lime and a parallel increase in the magnesia. On the forest type the ratio decreases through only the first three sections, rising slightly in the third foot.

TABLE 10  
*Magnesia in the different sections*

DEPTH	FOREST		UPLAND PRAIRIE		LOWLAND PRAIRIE	
	Old drift	Young drift	Old drift	Young drift	Old drift	Young drift
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	0.75	0.64	0.91	0.80	1.29	1.23
7-12	0.74	0.70	0.92	0.80	1.21	1.21
13-24	0.97	0.87	0.91	0.93	1.28	1.33
25-36	0.80	0.87	0.97	1.28	1.57	1.63
Average 1-36	0.84	0.80	0.93	1.00	1.35	1.39

TABLE 11  
*Relation of lime to magnesia in the different sections*

DEPTH	FOREST		UPLAND PRAIRIE		LOWLAND PRAIRIE	
	Old drift	Young drift	Old drift	Young drift	Old drift	Young drift
<b>A. Ratio of total lime to magnesia</b>						
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	1.5	1.8	1.4	1.7	2.3	1.8
7-12	1.3	1.4	1.3	1.6	2.0	1.7
13-24	1.0	1.1	1.2	1.4	1.3	1.5
25-36	1.3	1.3	1.0	1.7	1.3	1.4
Average 1-36	1.2	1.3	1.2	1.5	1.6	1.6
<b>B. Ratio of lime in form of silicate to magnesia</b>						
1-6	1.4	1.6	1.2	1.5	2.0	1.3
7-12	1.2	1.3	1.2	1.5	1.7	1.1
13-24	1.0	1.0	1.1	1.2	1.2	1.0
25-36	1.2	1.2	0.9	0.6	0.6	0.6
Average 1-36	1.2	1.2	1.1	1.1	1.2	0.9

### *Potash*

The distribution of potash (table 12-A) is fairly uniform for each type, the averages for the 3-foot section being practically the same for the two drifts, with the exception of the forest, which shows slightly higher amounts on the younger drift, averaging 1.96 per cent compared with 1.81 on the older. The average for the 3-foot section of all three types is 1.91 per cent for the older and 1.93 for the younger. The proportion shows no dependence upon the depth of the section.

*Soda*

Except on the lowland prairie the soda (table 12-B) shows no difference between drifts and but little variation with depth. For the entire 3-foot section the average content on the forest and upland prairie types is alike for both drifts.

On the lowland prairie it is considerably higher at all levels on the older drift, on which it is higher than on either the upland prairie or the forest fields, while on the younger drift it is lower than on either of these.

TABLE 12  
*Potash and soda in the different sections*

DEPTH	FOREST		UPLAND PRAIRIE		LOWLAND PRAIRIE	
	Old drift	Young drift	Old drift	Young drift	Old drift	Young drift

## A. Potash

<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	1.84	2.00	1.97	1.83	1.99	1.84
7-12	1.83	2.08	2.02	1.89	1.87	1.88
13-24	1.88	2.04	2.02	1.97	1.94	1.85
25-36	1.70	1.81	1.94	1.98	1.96	1.90
Average 1-36	1.80	1.96	1.98	1.93	1.94	1.87

## B. Soda

1-6	1.56	1.51	1.41	1.54	1.66	1.36
7-12	1.48	1.48	1.49	1.47	1.69	1.45
13-24	1.42	1.46	1.46	1.41	1.53	1.37
25-36	1.45	1.46	1.34	1.38	1.68	1.27
Average 1-36	1.46	1.47	1.42	1.43	1.62	1.34

*Phosphoric acid*

In all six groups phosphoric acid shows a decrease from the surface downward and with each type is the higher on the older drift and on both drifts it is highest in the lowland prairie (table 13).

This constituent was determined in the four sections from each of the 30 fields—120 samples in all (table 14 and fig. 5). From these it will be seen that there is less regularity than where composites of a large number of samples are used. In the forest fields the vertical distribution is more or less irregular, although the maximum in every field is found in the surface section, but on the upland prairie each of the ten fields shows the decrease with depth, and on the lowland prairie only two of the ten fail to conform to this regularity. From this it would appear that in the 3-foot section of practically every field on all three types on both drifts the phosphoric acid would show a decrease with depth if the samples analyzed were composites from a large number of

TABLE 13  
Phosphoric acid in the six groups of fields\*

DEPTH	FOREST		UPLAND PRAIRIE		LOWLAND PRAIRIE	
	Old drift	Young drift	Old drift	Young drift	Old drift	Young drift
inches	per cent	per cent	per cent	per cent	per cent	per cent
1-6	0.249	0.208	0.252	0.201	0.394	0.259
7-12	0.187	0.154	0.224	0.182	0.278	0.206
13-24	0.182	0.149	0.161	0.143	0.197	0.163
25-36	0.152	0.144	0.134	0.119	0.189	0.120
Average 1-36	0.184	0.158	0.178	0.151	0.241	0.172

\* On the basis of the carbonate-free inorganic portion of the soils and not on that of oven-dried soil as in table 14.

TABLE 14  
Phosphoric acid in the different sections from the thirty fields\*

DEPTH	OLD DRIFT						YOUNG DRIFT					
	Field I	Field II	Field III	Field IV	Field V	Average	Field I	Field II	Field III	Field IV	Field V	Average
Forest												
inches	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
1-6	0.236	0.216	0.220	0.280	0.213	0.233	0.213	0.175	0.207	0.162	0.213	0.194
7-12	0.182	0.160	0.178	0.223	0.156	0.180	0.178	0.140	0.159	0.115	0.143	0.147
13-24	0.150	0.162	0.194	0.197	0.178	0.176	0.162	0.147	0.147	0.131	0.128	0.143
25-36	0.124	0.159	0.134	0.188	0.143	0.150	0.162	0.162	0.110	0.131	0.137	0.140
Average 1-36	0.161	0.170	0.176	0.212	0.168	0.177	0.173	0.155	0.147	0.133	0.148	0.151
Upland prairie												
1-6	0.245	0.220	0.258	0.214	0.204	0.228	0.204	0.182	0.172	0.175	0.178	0.182
7-12	0.200	0.223	0.220	0.191	0.188	0.204	0.210	0.151	0.153	0.172	0.156	0.168
13-24	0.159	0.165	0.147	0.137	0.147	0.151	0.156	0.108	0.144	0.147	0.118	0.135
25-36	0.140	0.143	0.127	0.102	0.134	0.129	0.102	0.104	0.121	0.143	0.096	0.113
Average 1-36	0.174	0.176	0.171	0.147	0.159	0.165	0.155	0.126	0.142	0.154	0.127	0.141
Lowland prairie												
1-6	0.290		0.255	0.363	0.338	0.311	0.239	0.229	0.219	0.220	0.216	0.225
7-12	0.248	0.223	0.207	0.264	0.283	0.243	0.185	0.156	0.213	0.179	0.185	0.184
13-24	0.169	0.182	0.162	0.207	0.210	0.186	0.146	0.172	0.188	0.134	0.115	0.151
25-36	0.179	0.172	0.168	0.201	0.175	0.179	0.118	0.099	0.121	0.112	0.111	0.112
Average 1-36	0.206		0.187	0.240	0.232	0.214	0.159	0.154	0.175	0.148	0.142	0.156

\* On basis of oven-dried soil.

borings, although from place to place in the field there may be a departure. In an earlier study of prairie soils we have shown that a decrease in phosphoric acid from the first to the twelfth inch is characteristic of prairie soils (2).

Thus we find a consistent difference between the two drifts in their content of phosphoric acid, the older showing a higher content in each of the four sections on all three soil types. Also the average content in the 3-foot section, when individual fields on the same soil type but on different drifts are compared, is with but few exceptions higher on the older drift.

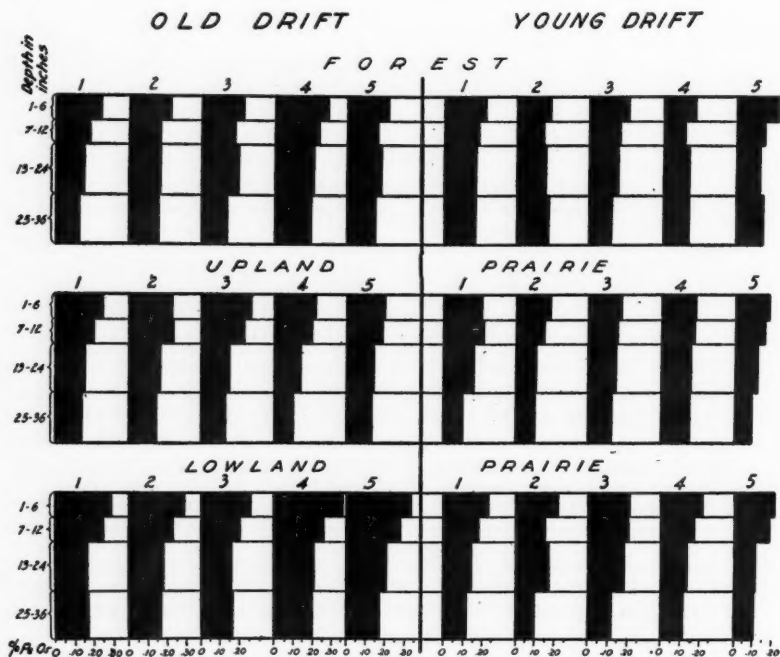


FIG. 5. DIAGRAM SHOWING DISTRIBUTION OF PHOSPHORIC ACID IN THE THIRTY FIELDS

#### *Ratio of phosphoric acid to organic carbon*

The concentration of phosphoric acid in the surface layers is connected with both the organic matter still remaining and that which has been converted into gaseous products (2, p. 496).

The relation between the phosphoric acid and the present content of organic matter will be evident from table 15 showing the ratio of organic carbon to total phosphoric acid. The ratio shows a wide range, from 3.3 to 30.4, and decreases rapidly with depth. In the case of the forest and upland prairie soils at all levels the ratio is somewhat higher on the younger drift. This

is due to the lower content of phosphoric acid and not to a greater amount of organic matter in the soil of the younger drift. In the lowland prairie no such regularity in the ratio is shown.

TABLE 15  
*Ratio of organic carbon to total phosphoric acid in the six groups of fields*

DEPTH	FOREST		UPLAND PRAIRIE		LOWLAND PRAIRIE	
	Old drift	Young drift	Old drift	Young drift	Old drift	Young drift
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	12.1	15.7	20.9	24.6	30.4	25.3
7-12	7.4	10.0	18.5	19.0	22.1	21.5
13-24	4.4	5.6	12.0	13.2	8.9	13.9
25-36	3.3	4.3	5.8	6.8	3.4	9.0
Average 1-36	5.8	7.6	12.5	13.9	12.8	15.4

### Nitrogen

On the forest type the variation in nitrogen from field to field, as well as the distribution from the surface downward, is much the same on the two drifts and there is little difference between the averages for the two.

TABLE 16  
*Nitrogen in the different sections from the thirty fields*

DEPTH	OLD DRIFT							YOUNG DRIFT						
	Field I	Field II	Field III	Field IV	Field V	Average		Field I	Field II	Field III	Field IV	Field V	Average	
Forest														
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>		<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	0.276	0.242	0.230	0.259	0.210	0.243		0.345	0.152	0.287	0.183	0.340	0.263	
7-12	0.192	0.083	0.121	0.135	0.080	0.122		0.151	0.058	0.138	0.067	0.173	0.117	
13-24	0.133	0.045	0.059	0.063	0.062	0.072		0.084	0.040	0.126	0.060	0.109	0.084	
25-36	0.062	0.043	0.027	0.033	0.031	0.039		0.048	0.034	0.050	0.041	0.047	0.044	
Average 1-36	0.143	0.083	0.087	0.098	0.079	0.098		0.128	0.060	0.129	0.075	0.137	0.106	
Upland prairie														
1-6	0.458	0.318	0.389	0.362	0.390	0.383		0.437	0.366	0.315	0.314	0.386	0.364	
7-12	0.300	0.273	0.291	0.265	0.331	0.292		0.379	0.210	0.272	0.264	0.265	0.278	
13-24	0.147	0.164	0.181	0.149	0.187	0.166		0.234	0.174	0.131	0.140	0.143	0.164	
25-36	0.050	0.064	0.061	0.052	0.063	0.058		0.083	0.053	0.063	0.065	0.068	0.066	
Average 1-36	0.192	0.174	0.194	0.171	0.203	0.187		0.242	0.172	0.162	0.165	0.179	0.184	
Lowland prairie														
1-6	0.855	0.505	0.605	1.012	0.955	0.786		0.525	0.427	0.396	0.391	0.484	0.445	
7-12	0.518	0.477	0.401	0.397	0.538	0.466		0.320	0.212	0.407	0.261	0.324	0.305	
13-24	0.165	0.139	0.167	0.131	0.157	0.152		0.107	0.085	0.316	0.102	0.128	0.148	
25-36	0.042	0.050	0.058	0.028	0.043	0.044		0.047	0.034	0.143	0.060	0.040	0.065	
Average 1-36	0.298	0.227	0.242	0.288	0.315	0.274		0.192	0.146	0.287	0.163	0.191	0.196	

On the upland prairie considerable variation from field to field is shown but this is similar on the two drifts and the averages for the five fields on each are very similar (tables 16 and 17, and fig. 6).

TABLE 17  
*Difference in nitrogen content of the three soil types\**

DEPTH	FOREST			UPLAND PRAIRIE			LOWLAND PRAIRIE		
	Old drift	Young drift	Difference	Old drift	Young drift	Difference	Old drift	Young drift	Difference
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	0.243	0.263	0.020	0.383	0.364	0.019	0.786	0.445	0.341
7-12	0.122	0.117	0.005	0.292	0.278	0.014	0.466	0.305	0.161
13-24	0.072	0.084	0.012	0.166	0.164	0.002	0.152	0.148	0.004
25-36	0.039	0.044	0.005	0.058	0.066	0.008	0.044	0.065	0.021
Average 1-36	0.098	0.106	0.008	0.187	0.184	0.003	0.274	0.196	0.078

\* Wherever the older drift is the richer the difference is shown in italics.

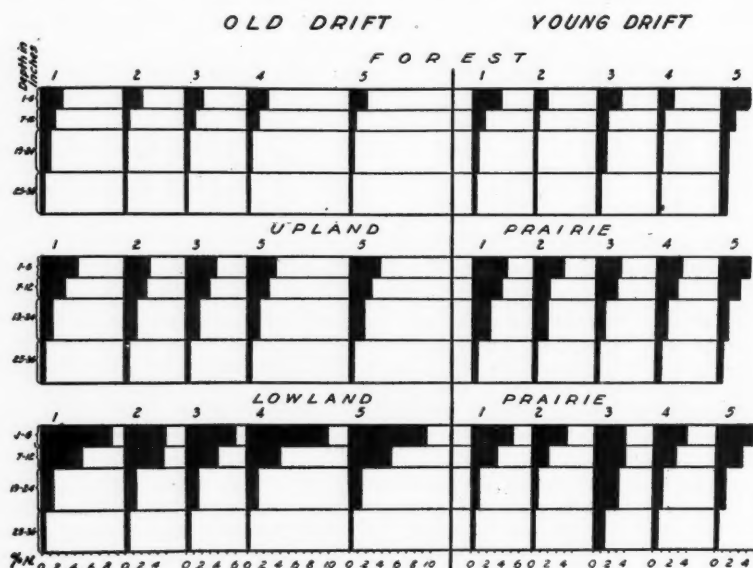


FIG. 6. DIAGRAM SHOWING DISTRIBUTION OF NITROGEN IN THE THIRTY FIELDS

On the lowland prairie fields which were in general far the richest in nitrogen a wide difference in the amounts of nitrogen was found in the surface foot on the two drifts, those on the older averaging 76 per cent the higher in the first 6 inches and 52 in the second. The conditions under which the soils of this type were developed, dealt with in the next section, furnish a possible expla-

nation for this difference, the accumulation of organic matter and nitrogen being parallel. The average amounts of nitrogen found in the second and third foot-sections on the two drifts are quite similar.

### *Organic carbon*

The organic carbon in the 24 group composites was determined by combustion with copper oxide in a current of oxygen (table 18). In order to decompose any carbonates present the samples were first moistened with phosphoric-acid solution and evaporated to dryness.

The differences in organic carbon agree with those in nitrogen. There is but little with the forest soils while with the prairies the old drift is the richer in the first two sections, the difference being especially marked in the lowland type. This may be attributed to obstruction of the drainage on the older

TABLE 18  
*Difference in organic carbon in the three soil types*

DEPTH	FOREST			UPLAND PRAIRIE			LOWLAND PRAIRIE		
	Old drift	Young drift	Difference	Old drift	Young drift	Difference	Old drift	Young drift	Difference
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	2.83	3.06	0.23	4.76	4.48	<i>0.28</i>	9.47	5.71	<i>3.76</i>
7-12	1.34	1.46	0.12	3.77	3.19	<i>0.58</i>	5.38	3.91	<i>1.47</i>
13-24	0.79	0.81	0.02	1.83	1.78	<i>0.05</i>	1.66	2.10	<i>0.44</i>
25-36	0.50	0.50	0.00	0.75	0.77	0.02	0.62	1.00	0.38
Average 1-36	1.12	1.19	0.07	2.28	2.13	<i>0.15</i>	3.23	2.64	0.59

\* Wherever the older drift is the richer the difference is shown in italics.

drift, due to the advance of the last ice sheet. The course of the streams before the Wisconsin glaciation was in a general southwesterly direction, but first the ice, and later the drift it left behind, blocked the previously existing drainage channels and forced the water to find outlets to the southeast. Before these new channels were fully developed the drainage was very incomplete and undoubtedly large areas were covered by standing water part of the season and surface material eroded from the surrounding higher land was deposited on the lowlands. Organic material would accumulate also through the growth of dense lowland vegetation and the deposition of its remains.

Little or no peat now remains on the older drift, and because of the shallowness of the water perhaps but little ever formed on it. On the younger drift the poorly drained areas are not so numerous as on the older and such as exist are more in the form of deep "pot holes" in which the conditions for the formation of peat have been favorable. So on this we usually find the lowland prairie forming a narrow band between the bog and the upland prairie.

If at the time of the retreat of the last ice sheet part of the organic carbon now found in the surface soil of the lowland prairie was derived from the eroded surface of the surrounding high land, this would account for some of the differences now found. The surface of the older drift, undisturbed by the Wisconsin ice, would carry a surface soil more or less rich in organic carbon while the material of the till freshly exposed by the retreating ice front would carry very little. Accordingly, the eroded material deposited on the lower-lying levels of older drift would be much richer in organic matter than that on the younger.

*Ratio of organic carbon to nitrogen*

The ratio of organic carbon to nitrogen shows no regular difference from drift to drift (table 19).

TABLE 19  
*Ratio of organic carbon to nitrogen in the three soil types*

DEPTH	FOREST		UPLAND PRAIRIE		LOWLAND PRAIRIE	
	Old drift	Young drift	Old drift	Young drift	Old drift	Young drift
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	11.6	11.6	12.4	12.3	12.0	12.8
7-12	11.0	12.4	12.9	11.4	11.5	12.8
13-24	11.0	9.6	11.0	10.8	10.9	14.1
25-36	12.9	11.3	12.9	11.6	14.1	15.3
Average 1-36	11.7	10.3	12.1	11.4	12.2	14.1

*Water of constitution*

The water of constitution shows no dependence upon the age of the drift. A statement of the volatile matter of the soil has in itself very little significance, but when once the organic carbon has been determined the organic matter may be computed with a fair degree of reliability by the formula given above, viz., organic matter = organic C  $\times$  1.724, and the difference between the volatile matter and the sum of the organic matter so determined and the carbon dioxide expresses the water of constitution, the water not expelled at 110°C. but driven off below a dull red heat. As this value is found by difference any errors in the determination of the organic carbon or carbon dioxide will be reflected in the percentage found for the water of constitution.

*Color*

Comparisons were made of the colors of all the samples. For this purpose 25-gm. portions of the fine earth were placed in small porcelain dishes, moistened and allowed to stand for an hour. Then all the moistened samples were arranged in order of color, the darkest being placed at one end and the lightest-colored at the other.

No distinct and characteristic difference between the drifts was found except that in the third foot of the upland prairie the fields on the older drift had a distinctly reddish tint in contrast with the gray or yellowish gray of the younger (15, p. 59). On the forest and lowland prairie fields no characteristic difference was observed—the reddish tint being absent even from

TABLE 20  
*Volatile matter, organic matter, and water of constitution of the three soil types*

DEPTH	FOREST		UPLAND PRAIRIE		LOWLAND PRAIRIE	
	Old drift	Young drift	Old drift	Young drift	Old drift	Young drift
A. Volatile Matter*						
<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	6.41	6.71	10.52	9.38	20.34	11.68
7-12	3.73	4.15	8.58	7.80	12.12	9.61
13-24	3.32	3.77	6.07	5.34	5.41	6.43
25-36	2.66	2.89	3.73	5.25	4.08	5.87
Average 1-36	3.68	4.03	6.45	6.39	8.57	7.31
B. Organic matter ( $C \times 1.724$ )						
1-6	4.87	5.18	8.20	7.72	16.32	9.84
7-12	2.31	2.52	6.50	5.50	9.27	6.74
13-24	1.36	1.40	3.15	3.07	2.86	3.62
25-36	0.86	0.86	1.29	1.33	1.07	1.72
Average 1-36	1.94	2.04	3.93	3.67	5.57	.54
C. Water of constitution						
1-6	1.47	1.45	2.24	1.58	3.72	1.35
7-12	1.37	1.57	2.00	2.25	2.66	2.30
13-24	1.91	2.33	2.86	2.14	2.49	2.27
25-36	1.75	1.98	2.41	2.86	2.17	3.11
Average 1-36	1.69	1.94	2.46	2.30	2.62	2.40

\*  $CO_2$  included in volatile matter.

the third foot. So far as the intensity of the dark color is concerned the only distinct difference between the two drifts observed was its somewhat more pronounced development on the younger drift in the case of the surface section of the upland prairie, just the opposite to that reported by Burke and Kolbe, who state that "The Kansan drift has generally a darker color than the Wisconsin" (4, p. 21).

#### *Reaction and calcareousness*

In the case of all the field samples the reaction was ascertained by the Truog method and the carbon-dioxide content determined (tables 21 and 22). Wherever a sample gave a distinctly acid reaction the carbonate content was

TABLE 21

*Calcareousness—degree of acidity (a) of acid samples and carbonate content (b) of others*

DEPTH	OLD DRIFT					YOUNG DRIFT				
	Field I	Field II	Field III	Field IV	Field V	Field I	Field II	Field III	Field IV	Field V
Forest										
<i>inches</i>										
1-6	med.	str.	str.	str.	med.	sl.	sl.	med.	sl.	str.
7-12	med.	str.	med.	str.	str.	sl.	sl.	str.	sl.	med.
13-24	sl.	str.	str.	med.	str.	med.	sl.	str.	sl.	med.
25-36	sl.	v.sl.	med.	sl.	str.	med.	sl.	med.	v.sl.	sl.
Upland prairie										
1-6	med.	str.	med.	str.	med.	med.	sl.	med.	med.	med.
7-12	med.	med.	med.	str.	med.	med.	v.sl.	med.	med.	sl.
13-24	str.	med.	str.	v.str.	str.	sl.	0.39	0.79	sl.	sl.
25-36	sl.	med.	med.	str.	med.	v.sl.	3.55	7.12	v.sl.	1.23
Lowland prairie										
1-6	sl.	0.19	med.	0.32	2.10	5.06	med.	med.	sl.	sl.
7-12	sl.	0.18	sl.	0.20	1.52	5.47	sl.	sl.	sl.	sl.
13-24	0.09	0.12	v.sl.	0.01	0.36	5.67	v.sl.	v.sl.	v.sl.	v.sl.
25-36	0.18	1.11	2.27	0.02	5.82	9.05	0.24	0.08	2.35	0.04

(a) v.sl. = very slight; sl. = slight; med. = medium; str. = strong; v.str. = very strong, as determined by the Truog method.

(b) Computed from CO<sub>2</sub> as per cent CaCO<sub>3</sub>.

TABLE 22

*Carbon dioxide obtained from foot sections of 15 fields, all of which were acid throughout the 3-foot profile*

DEPTH	OLD DRIFT							YOUNG DRIFT						
	Field I	Field II	Field III	Field IV	Field V	Average		Field I	Field II	Field III	Field IV	Field V	Average	
Forest														
<i>foot</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>		<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	
1	0.064	0.048	0.062	0.070	0.072	0.063		0.098	0.078	0.069	0.048	0.064	0.071	
2	0.032	0.084	0.006	0.064	0.080	0.053		0.048	0.036	0.040	0.044	0.044	0.042	
3	0.046	0.076	0.020	0.056	0.060	0.051		0.026	0.050	0.036	0.108	0.042	0.052	
Average	0.047	0.069	0.029	0.063	0.071	0.056		0.057	0.055	0.048	0.067	0.050	0.055	
Upland prairie														
1	0.086	0.064	0.074	0.092	0.082	0.079								
2	0.045	0.056	0.075	0.064	0.046	0.057								
3	0.031	0.035	0.036	0.016	0.024	0.034								
Average	0.054	0.052	0.062	0.057	0.051	0.057								

found negligible, but the reverse does not hold true, a few of the neutral samples showing an equally small content of carbon dioxide.

The carbon dioxide obtained from samples with an acid reaction is not to be attributed to contained carbonate but to the decomposition of organic matter. In nearly every field in which all four samples from the 3-foot section gave an acid reaction the most carbon dioxide was obtained from the surface section, the one richest in organic matter, although this was in general the most acid, as is well illustrated by table 22.

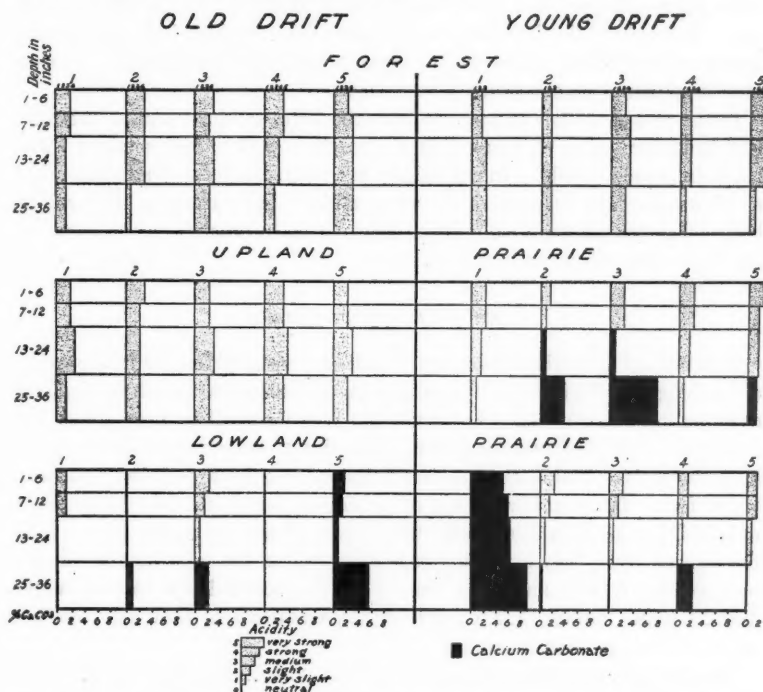


FIG. 7. DIAGRAM SHOWING THE REACTION AND CARBONATE CONTENT IN THE THIRTY FIELDS

While both the reaction and the carbon-dioxide content were determined in the case of every sample, the lime supply is best indicated in the form of the degree of acidity in the case of the acid samples and the amount of carbonate, computed as calcium carbonate, in those of neutral reaction (fig. 7).

With the forest type no distinct difference between drifts was shown, all four levels from the 3-foot section in the ten fields showing an acid reaction, but on the upland prairie there was, on the whole, a better supply of carbonate on the younger drift. The subsoil in three fields, no. II, III and V, on the latter showed a neutral reaction and an appreciable amount of carbonate,

while in all the fields on the older drift it was acid. The greater degree of leaching in the forest type on the Young Drift, compared with the upland prairie of the same age, is to be attributed to the coarser texture of the former, permitting more rapid percolation and causing less water from the rain and snow to be retained in the surface layers and later returned to the air by transpiration and direct evaporation.

In the case of the upland prairie the difference in carbonate content between the two drifts is not to be explained by any difference in texture or topography, these being alike on both drifts, but is to be attributed to the difference in age. Throughout the first 3 feet in the forest fields leaching had been equally severe on both drifts. Even on the upland prairie the difference, in so far as most crop plants are concerned, is very slight.

In the case of the lowland prairie fields the drifts are quite similar, the third foot being neutral in all cases while the reaction of the upper sections varies much from field to field. In one field on each drift much carbonate was found at all levels. The nearness of the water-table to the surface on this type on both drifts has generally so checked leaching as to obscure any influence of age that might otherwise have been shown.

#### *Depth of leaching of carbonates*

It is evident from the above that if a characteristic difference in the extent of leaching is to be found in the case of the two areas compared the depth of examination must exceed 3 feet. On the Wisconsin till in Iowa Alden and Leighton (1, p. 88) found the depth of leaching to extend only to 2 to 3 feet from the surface, and in many places limestone pebbles were found at or near the surface. In contrast with this, on the Iowan they found the average depth of leaching to be from 4 to 6 feet,<sup>2</sup> with limestone pebbles mostly absent from the leached layer, they averaging only 3 per cent of the total number of pebbles present (1, p. 81 and 184). In the examination of 165 exposures in cuts and 250 auger borings they found less than one-tenth to show effervescence at a depth of less than 3 feet (1, p. 82).

Our five upland prairie and five forest fields on the older drift, in which 200 borings were made in securing samples, were found leached beyond the 3-foot level, and so do not differ in this respect from Alden and Leighton's description of the Iowan. On our five forest fields on the young drift, in which 100 borings were made, the leaching throughout the 3-foot section appears as complete as on the older drift. Even on the upland prairie on the latter drift two of the fields (I and II in table 21) showed almost as little evidence of carbonate, but the third foot in two was very calcareous and the second foot sufficiently so to indicate that on each of these some of the 20 borings had penetrated the unleached layer. Thus the leaching of the older and younger drifts that

<sup>2</sup> This depth of 4 to 6 feet generally includes 1 to 2.5 feet of leached soil and loess-like clay overlying 3 to 3.5 feet of leached till.

TABLE 23  
*Depth of leaching of carbonates*

	OLD DRIFT					YOUNG DRIFT				
	Field I	Field II	Field III	Field IV	Field V	Field I	Field II	Field III	Field IV	Field V
Forest										
Depth of leaching (feet).....	4.5	4.5	4.0	5.5	3.8	4.5	4.0	3.6	3.8	5.0+
Calcareousness of third foot*.....	Slight acidity	Very slight acidity	Medium acidity	Slight acidity	Strong acidity	Medium acidity	Slight acidity	Medium acidity	Very slight acidity	Slight acidity
Upland prairie										
Depth of leaching (feet).....	3.6	4.8	4.3	3.7	3.6	4.5	2.7	2.5	4.5	2.9
Calcareousness of third foot*.....	Slight acidity	Medium acidity	Medium acidity	Strong acidity	Medium acidity	Very slight acidity	3.55 per cent carbonate	7.12 per cent carbonate	Very slight acidity	1.23 per cent carbonate

\* From table 21.

we have found in Rice County is similar qualitatively but not quantitatively to what Alden and Leighton report for Iowa. In this connection it should be emphasized that these writers were contrasting the Des Moines lobe as a whole with the older drift to the east, while we are intentionally confining our comparisons to a part of the extreme western edge of the Iowan with the adjacent and almost extreme eastern edge of the Wisconsin. Their reports do not indicate that they have sought to ascertain whether distinct differences in depth of leaching might be found upon the Des Moines lobe itself when one part is compared with another, as for example the eastern with the central or western.

If at the time of our collection of samples we had had before us the results of Alden and Leighton's studies we would have carried each of the borings down to the unleached till, but at that time our purpose was not to make any more exhaustive comparison of the carbonates than of various other important constituents. However, we have revisited the area very recently—since the advent of the winter—for a hasty exploration for the depth of leaching, making a boring or two in each of the twenty upland fields, as well as in many of those intervening, and examining the exposures in recent road cuts. Table 23 shows the depths at which effervescence was found in the various fields, with the use of cold dilute hydrochloric acid.

The upland prairie fields on the Wisconsin showed an average of 3.4 feet and on the older drift of 4.0 feet. The forest showed an average of 4.0 feet on the former if we omit field V, and of 4.5 feet on the latter. In that field we found a layer of sand and gravel at a depth of about 5 feet to underlie all the portion sampled, and down to this coarse layer no sign of carbonates was found.

#### DIFFERENCES IN COMPOSITION ACCORDING TO SOIL TYPE

The lowland prairie fields are the finest in texture and highest in nitrogen, organic carbon, phosphoric acid, magnesia and lime (both total and non-carbonate). The upland prairie occupies an intermediate position in regard to texture, content of nitrogen, and organic carbon. The forest is coarsest in texture and slightly the highest in silica and lowest in alumina. In potash and soda there is no distinct difference.

#### RELATION OF COMPOSITION TO DEPTH OF SECTION

The relations found to exist among the successive levels are not unusual. With increase in depth there is in general a decrease in the fineness of texture, as expressed by the moisture equivalent, but in more than half of the upland prairies no distinct difference was found between the upper and lower sections of the surface foot. In the forest fields the second foot shows a moisture equivalent equal to that of the overlying 6-inch layer, and on part of the lowland prairies there is little difference between the second and third foot-sections.

With an increase in depth nitrogen and organic carbon decrease rapidly, and phosphoric acid to a less extent, while carbonates if present at all, tend to increase. Where carbonates are absent from the 3-foot profile the degree of acidity is not distinctly related to the depth. Compared on the basis of the carbonate-free non-volatile portion of the soil, iron is found to increase with depth and magnesia to a less marked extent, while silica, alumina, titanium and potash remain practically constant. Soda is a little the highest in the surface section and non-carbonate lime, on the prairie types, tends to decrease with depth.

#### RELATION OF COMPOSITION TO AGE OF DRIFT

From the above detailed comparison of the properties and composition it is evident that to a depth of 3 feet the two drifts are very similar. Only in the content of carbonates, phosphoric acid, iron and titanium, as well as in the distribution of the gravel particles, do the differences appear of sufficient magnitude to merit further consideration in this discussion.

The first sign of age is to be sought in the extent of leaching of carbonates, in which the differences found are a distinct disappointment. On the younger drift the depth in the forest type averages about 4.0 feet and on the upland prairie 3.4, compared with 4.5 in the forest and 4.0 in the prairie on the older.

Iron and titanium are slightly higher on the older drift. As the alumina is not correspondingly higher, or the silica, magnesia, etc. lower, we are not justified in attributing this difference to an enrichment of the iron through the leaching out of the other constituents. The occurrence of a larger proportion of iron minerals among the gravel particles of the older drift suggests a higher original iron content.

Phosphoric acid is characteristically higher in the upper layers of the older drift, but this is to be attributed to the upward translocation by plants rather than to a concentration through leaching, if we assume that the original till on both drifts was alike in this constituent.

No characteristic differences are found in silica, alumina, magnesia, non-carbonate lime, potash, soda, nitrogen or organic carbon.

The gravel shows only a slight difference; on the older drift there is a more marked difference between the third foot and the overlying sections, as though weathering had proceeded farther on this.

While what differences were found in the gravel and in the chemical composition of the fine earth agree with the assumption that the drift in the eastern part of Rice County is the older, they are far too small to have suggested a difference in age, and they might be regarded as so slight as even to cast doubt upon the correctness of the line which Leverett has traced in Rice County as the boundary between the drifts, and hence upon the location of our western fields on the younger drift, were the boundary of the Late Wisconsin not so distinctly marked by the characteristic terminal moraine (fig. 3.)

Our results are not in accord with those found by Brown in comparing the soils on the Iowan and Late Wisconsin glaciations in Iowa and by Hopkins and Pettit in their earlier and more extensive studies in Illinois, in which they dealt with the Illinoian, Early and Late Wisconsin and possibly also with the Iowan.

Hopkins and Pettit (8), using samples from three levels, 1-6, 7-20, 21-40 inches, found a decrease in potash, phosphoric acid, and nitrogen to be associated with an increase in the age of the drift upon which the soils occur, the potash showing the most striking differences. Brown (3), using similar sections found the soils on the Late Wisconsin richer in potash, phosphoric acid, total lime, nitrogen and organic carbon than those on the Iowan.

We purposely selected fields so close to the eastern boundary of the younger drift in order to avoid differences in soil composition that might have resulted from differences in climate, in vegetation, or in both, as these would be liable completely to mask any differences in composition due to difference in age, if the sampled areas are very far apart. If we had compared samples taken from areas much farther removed from one another we would have found much greater differences in some constituents, as is evident from studies by P. R. McMiller and P. M. Harmer, which are to appear in later numbers of this series, but these differences we attribute to other causes than the greater age of the drift east of the Des Moines Lobe.

#### SUMMARY

1. A comparison was made of the composition and properties of the soils developed on neighboring areas of two drift sheets in southeastern Minnesota—the Des Moines Lobe of the late Wisconsin and the older glaciation exposed just to the east of this and referred to as the Iowan. The original till of these appears to have been very similar chemically and physically, and the areas compared are so near one another that they must have been subjected to the same climatic influences since the recession of the last ice sheet.

2. On each drift 15 virgin fields were sampled—5 on each of three soil types, viz., Carrington loam, naturally covered with deciduous forest, and Carrington silt loam and Fargo silt loam, both naturally in prairie. The samples were taken to a depth of 3 feet, in four sections—1-6, 7-12, 13-24 and 25-36 inches, 20 borings in each field.

3. Comparing the three soil types the Carrington loam (forest) was found coarsest in texture and slightly the highest in silica and lowest in alumina, the Fargo silt loam (lowland prairie) the finest in texture and highest in nitrogen, organic carbon, phosphoric acid, magnesia and lime, while the Carrington silt loam (upland prairie) occupies an intermediate position in texture and content of nitrogen and organic carbon. In potash and soda there is no distinct difference.

4. Comparing the four successive levels an increase in depth is found to be accompanied generally by an increase in coarseness of texture, regularly

by a decrease in nitrogen and organic carbon and less regularly by a decrease in phosphoric acid. In fields where carbonates were encountered they increased with depth, but where they were absent throughout the 3-foot section the degree of acidity is not distinctly related to the depth. When comparisons are made on the basis of the carbonate-free, non-volatile portion of the soil, with increase in depth iron and magnesia are found to increase slightly, non-carbonate lime to decrease slightly, and silica, alumina and potash to remain practically constant. The leaching effect upon the mineral constituents originally present in the drift has been practically confined to the carbonates.

5. Comparing the soils from the two drifts, type by type and level by level, no distinct differences are found in texture, or content of silica, alumina, potash, soda, magnesia, non-carbonate lime, nitrogen, and organic carbon. The soils on the older drift are considerably richer in phosphoric acid, especially in the upper levels, and contain appreciably more iron and titanium. The carbonates have been so thoroughly leached from the whole 3-foot section in the forest fields on both drifts that a distinctly acid reaction is found at all levels. The same holds true of the upland prairie on the older drift, but on part of the fields on the younger drift carbonates are found in the third and even in the second foot. A later exploration of the levels below the third foot shows that on both the upland soils types the depth of leaching out of carbonates is in general somewhat greater on the older drift.

6. It would appear that the only distinct influence that the greater age of the Iowan drift has been able to exert upon the soils developed upon it is confined to the leaching out of carbonates to a greater depth and possibly an enrichment of the surface layers in phosphoric acid through the agency of plants.

7. It appears that in a comparison of the chemical composition of the soils on drift sheets neither of which is older than the Iowan the only distinct difference that may justly be attributed to the difference in age is confined to the relative depth of leaching of carbonates. The greater concentration of phosphate near the surface on the older drift, observed in the areas compared in this study, may not be found elsewhere.

8. It appears probable that the marked differences in content of nitrogen and organic carbon reported from comparisons of soils on Wisconsin and Iowan drifts are due to differences in the vegetation and climate that have been associated with the particular portions of the two sheets employed in the comparison.

9. Both the Iowan and Wisconsin glaciations appear to have been too recent to allow sufficient time for any appreciable leaching out of the original content of potash, of non-carbonate lime and magnesia, or of silica, at least in the case of the till or of the finer-textured assorted material from this.

10. The question is also raised as to whether there is any satisfactory evidence of the leaching out of the four constituents just mentioned, even in the case of the oldest drift sheets.

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## PLATE 1

## ILLUSTRATIONS SHOWING THE CHARACTER OF VEGETATION ON THE FOREST TYPE

FIG. 1. Field V on the Old Drift; the samples were collected on the portion with the trees still standing.

FIG. 2. In the midst of Field IV on the Young Drift, showing the cover of leaves on the forest floor.



FIG. 1



FIG. 2

PLATE 2

ILLUSTRATIONS SHOWING THE CHARACTER OF THE ONLY REMAINING UNPLOWED TRACTS ON  
UPLAND PRAIRIE

FIG. 1. Field V on the Young Drift consists of the long unplowed strip in the fence line between farms.

FIG. 2. Roadside strip on the Young Drift; Field II.

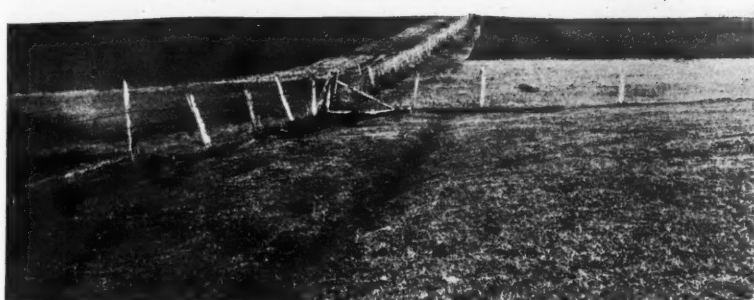


FIG. 1



FIG. 2

PLATE 3

ILLUSTRATIONS SHOWING THE TOPOGRAPHY OF THE LOWLAND PRAIRIE FIELDS

FIG. 1. Field III on the Old Drift, the broad roadside strip at the left.

FIG. 2. Field II on the Young Drift. It lies at the foot of the slope and to the right of the fence.



FIG. 1

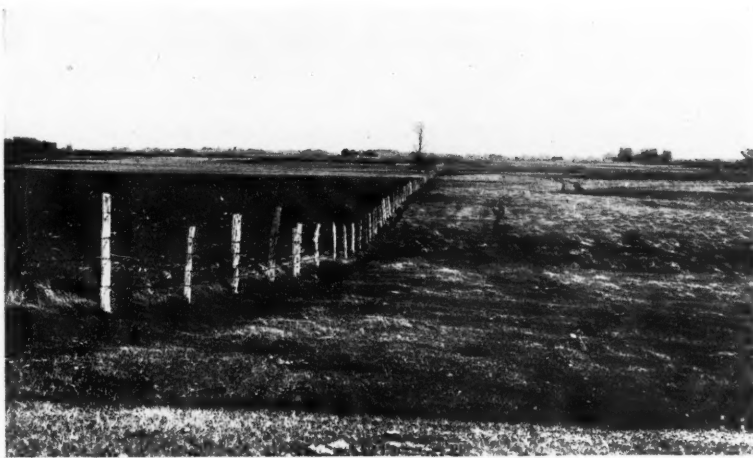
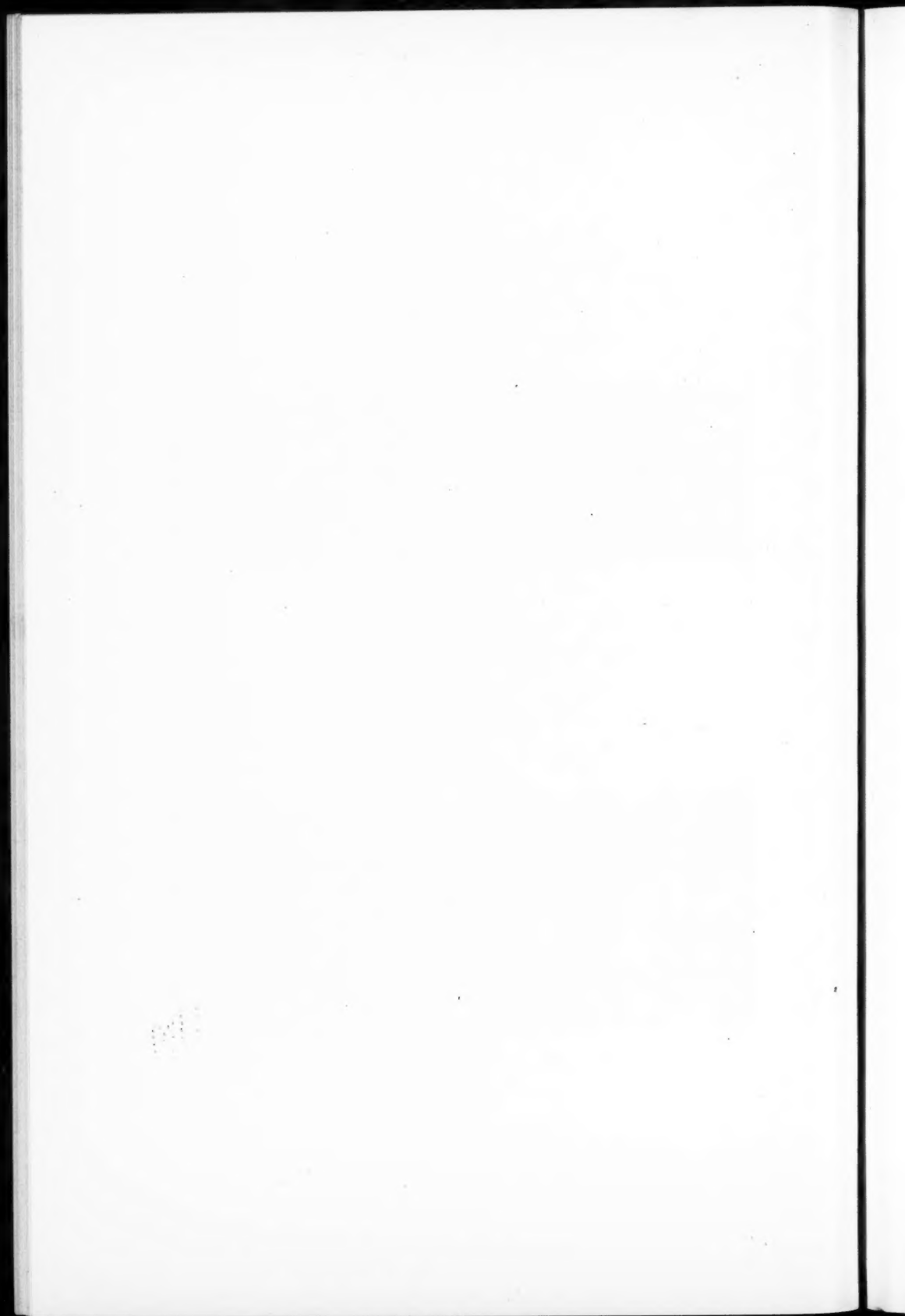


FIG. 2



## A PITLESS LYSIMETER EQUIPMENT

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The use of outdoor lysimeters offers an attractive field for research in soil chemistry. The cost of installation, however, is a deterrent to a more general utilization of this type of equipment. It is necessary to afford protection to the receivers provided for the collection of the leachings and to insure against undesirable temperature ranges. If the equipment is extensive, it is also desirable to provide for the comfort and efficiency of the persons engaged in weighing, or measuring, and sampling the percolations. The expense of constructing a substantial concrete cellar or terrace walls is one of the principal factors in the cost of such an installation. At the present time there are in operation at the University of Tennessee Agricultural Experiment Station, three distinct types of concrete structures devoted to studies upon the leachings from soils subjected to experimental treatment.

The first and second installations have been described in two papers by the writers of this article (1, 2). The third installation has not been described. Recently, still another equipment has been installed. This last equipment is distinctive, in that no surface or sub-surface concrete enclosure is required. A description and illustrations of it are here offered, with the hope of stimulating research along lysimeter lines by pointing out that the tanks of this type can be installed at relatively low cost. Even under the prevailing abnormal conditions a 12-unit system has been installed at a total cost of \$500; while a 34-tank system involving tanks of greater area and less depth has been contracted for at a total cost of about \$1400. As illustrated in plate 1 and figure 1, each lysimeter is composed of a pair of heavy (14-gauge) cylindrical galvanized "ingot iron" tanks. The soil-container is 6 feet 3 inches long, with an inside diameter of 12 inches. The bottom of this tank is slightly conical in shape, with a flexible block-tin tube outlet. Around the outside of the top is riveted a  $\frac{1}{4}$  by 1-inch iron band. Soldered to the outside of the tank and just under this band is a 2-inch copper rim, or water shed, as a protection against movement of rainfall down the outside of the tank. Twisted iron handles, or loops, also are fastened to the inside of the inner tank at the top, in order to facilitate lifting when desired. The inside soil-container tank slides into the outer tank which is 7 feet and 3 inches deep. On the inside of the outer tank are riveted three iron lugs, or supports, upon the upper ends of which the inside tanks rest, the bottom of the inside tank

being 1 foot from the bottom of the outside tank. The percolates from the inside tank are caught in this reservoir of 1 foot depth and slightly greater diameter.

The bottom of the outside tank is on the bevel, though the sides of the tank extend below to a horizontal plane and rest upon a 6-inch concrete base 15 inches square. This concrete base prevents settling of the sharp edges and thus insures against any disrupting strain upon the bottom of the outside tank. A hole is drilled in the side of the outer tank at the lowest point of the beveled bottom for insertion of a block-tin L which is heavily soldered to the tank wall and to

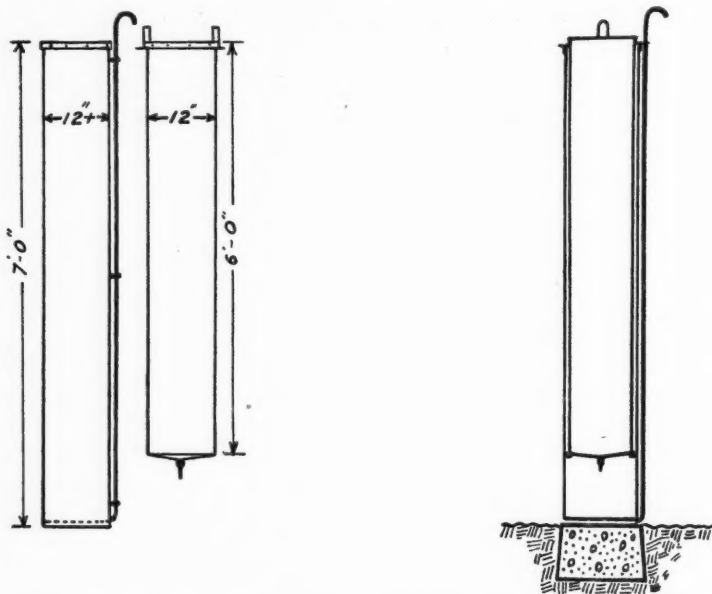


FIG. 1. SKETCH SHOWING INTERIOR ADJUSTMENTS FOR INSERTION OF THE SOIL-CONTAINER TANK IN THE OUTSIDE RESERVOIR TANK AND CONCRETE BASE

the end of the perpendicular  $\frac{1}{4}$ -inch galvanized iron pipe which extends several inches above the ground level. To the top of this perpendicular tube, which is attached to the exterior side of the outside tank, a block-tin goose-neck is soldered. A slit is provided in the copper rim to permit passage of the  $\frac{1}{4}$ -inch upright galvanized iron pipe. The leachings, which pass down through the inner tank to the outer tank reservoir are pumped up this upright goose-necked pipe into individual asphaltum-coated galvanized-iron containers, one of which is shown attached to the tank and pump in plate 2. These leaching-containers have convex tops tightly soldered around the edges and two necks, one for in-flow of leachings and one for suction outlet to the foot pump. The

tops of the containers are provided with 6-inch crimped lids which can be made airtight by means of a vaseline-paraffin mixture seal; and which also afford means of ready access for examining, painting, or coating the interiors.

In placing the soil contents, a perforated disc or asphaltum-coated wire cloth strainer is placed over the central outlet of the inner tank and a thin layer of coarse sand introduced. As definite amounts of soil are added, careful and uniform tamping should be insured by means of a circular tamp of slightly less diameter than the tank. Should a periodic study of the different zones of the soil column be contemplated, a  $\frac{1}{16}$  or  $\frac{1}{8}$ -inch mesh asphaltum-coated wire-cloth disc may be inserted at the desired depths. This insures definite demarcation of the prescribed zones at the time of dismantling. By proper duplication, this type of equipment adapts itself to a continuous study of the periodic and progressive residual effects induced by particular treatments, according to indications afforded by the leaching data. When it is desired to make such residual studies upon the different zones, a steel bar is placed through the iron-loop handles of the inner tanks and they are hoisted and removed by means of the block and tackle and tripod device shown in plate 2 (fig. 2). The soil-filled tanks are then placed in a horizontal position to facilitate removal of soil and subsoil zones. The tanks are then available for new or repetition studies.

While the illustrated tanks are all of 12-inch diameter and 6 and 7-foot depths, the principle may be adapted as applying to larger diameters and lesser depths. As previously stated, an additional set of this character are being placed shortly, upon bases already provided.

Local conditions, as to periodicity and volume of rainfall and depth of frost line, of course, are to be considered in the use of this type of equipment. In those climates where freezing below the 1-foot line over extended periods would be anticipated, there would be probably a minimum of winter leachings, which would mean little, if any, required attention or discomfiture during the intensely cold weather. On the other hand, in moderate climates where the soil seldom freezes for any length of time and where winter rains result in leachings, the short period of exposure experienced while pumping the leachings for conveyance to the laboratory would not constitute a serious objection. While the volumes of the leachings are not to be observed by the eye, nevertheless, knowing the relationship between rainfall and leachings, the record of precipitation will serve as an adequate guide relative to the frequency of removal of leachings.

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PLATE 1

- FIG. 1. Outside tank and inside soil-container tank.  
FIG. 2. Outside tank with inside tank in place.

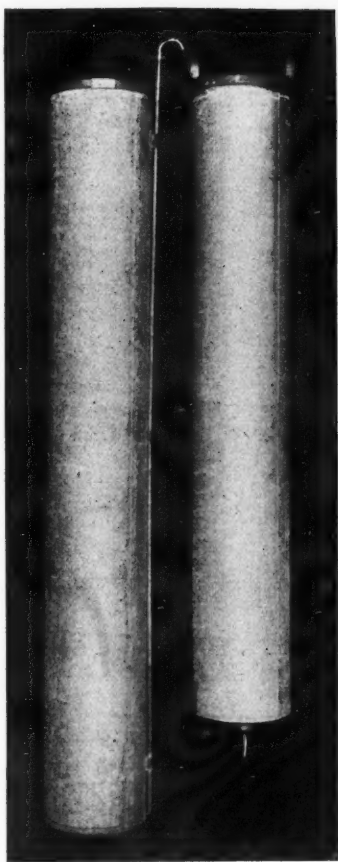


FIG. 1



FIG. 2

PLATE 2

FIG. 1. Illustration showing the arrangement of the tanks after placing, the inside tanks and rims masking the outside tanks, and the apparatus for pumping up the leachings

FIG. 2. Tripod and tackle and pulley device for removing the soil-container inside the tank when dismantling for periodic studies.

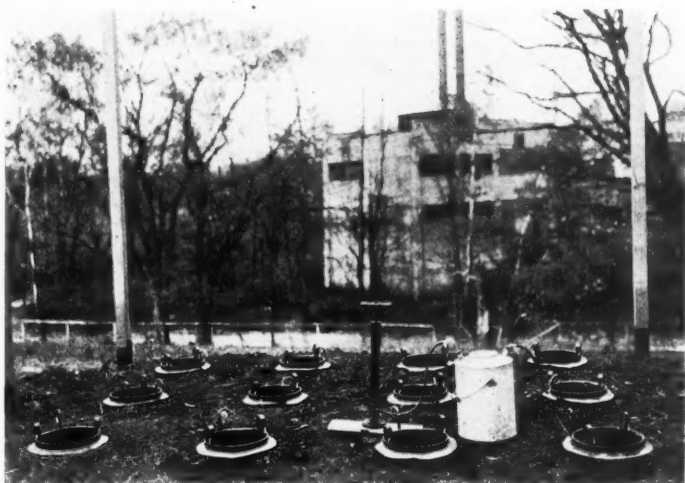


FIG. 1

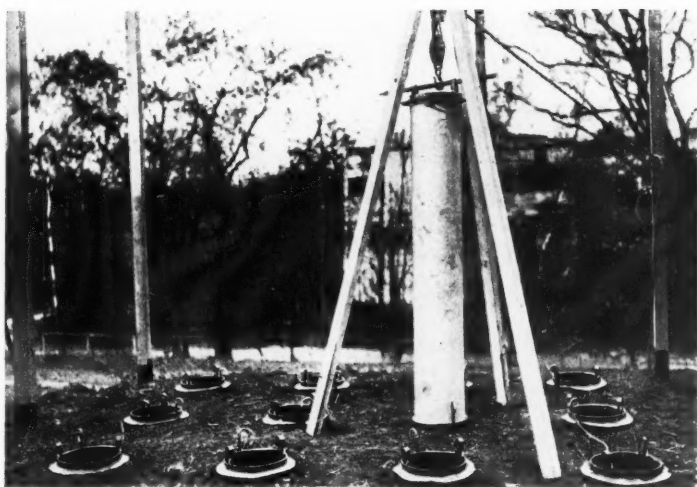
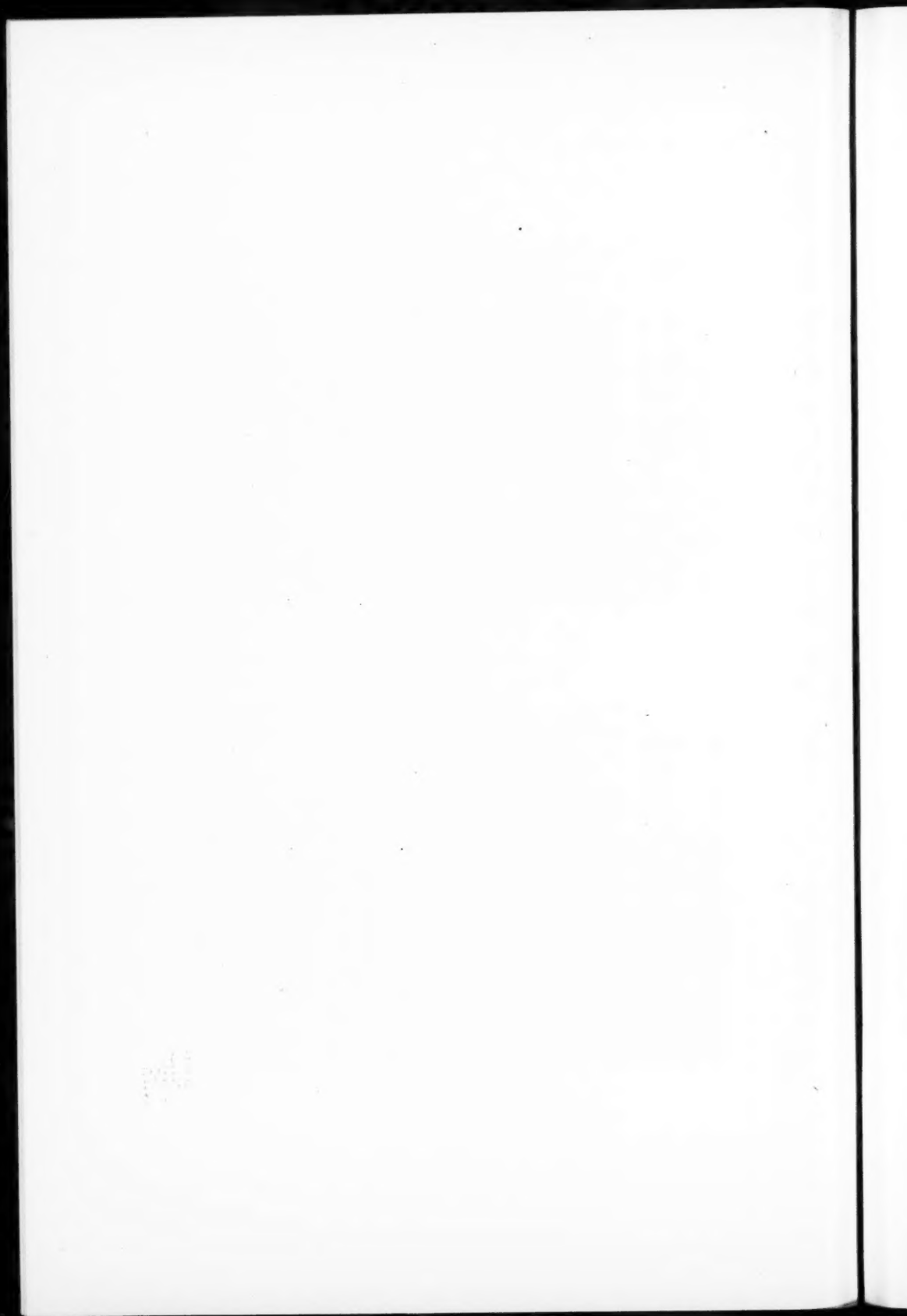


FIG. 2



## THE MOVEMENT OF SOIL MOISTURE

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### I. INTRODUCTION

The quantity and diversity of the experimental work that has been done on soil moisture attests the importance of the subject. The motive, as with other phases of agricultural research, has been primarily economic in character and for that reason little attention has been given to the theoretical aspect of the problem, although a number of excellent articles have been written from this point of view. As experimental facts accumulate, however, the need for a generalization increases. With this thought in mind and with the hope that those who are interested will offer helpful suggestions, the authors have been led to prepare this short article as an introduction to the subject.

The experimental curves presented below are not wholly conclusive and it is possible that certain modifications in the original hypotheses may be found necessary, but the general conformity in theory and experiment would seem to lend a considerable amount of evidence to the approximate validity of the assumptions that have been made.

The first section is merely an attempt to outline in a language more generally understood the trend of thought embodied in the mathematical development of the second part. The differential equation (4) is the direct consequence of equation (1), which contains the assumptions which have been made, and equation (2), which is a well known equation in hydrodynamics, the validity of which in this case will not be questioned. To those who are unfamiliar with the methods of the calculus an equation such as (4) does not convey an intelligent idea, and the methods which are resorted to in applying it to experimental facts will likewise be somewhat vague. It is hoped, however, that some satisfaction may yet remain by passing over this part of the discussion, and judging of its fruitfulness by a comparison of the graphical representation of its predictions with the graphical experimental facts.

It should be pointed out that the trend of natural phenomena may be influenced by numerous agencies or factors and an attempt to introduce them all

<sup>1</sup> The formal development of the mathematical material of this paper was made by the senior author as an outgrowth of the earlier work of the junior author, who has assisted in clarifying this material for publication.

explicitly in a mathematical formula purporting to describe such phenomena would be foredoomed to failure. If, however, minor factors may be temporarily ignored and the major ones divided into a small number of groups, it may thus be possible to construct in the imagination an ideal problem which in reality may differ only slightly from the actual case but the solution of which may lie within our power.

Let us, therefore, regard the soil as a rigid, homogeneous configuration of heterogeneous individual particles which does not change with the time, but through which the moisture moves; and we shall attempt to specify the density of the moisture in the soil, i.e., the aggregate amount in unit volume of soil, in terms of space coordinates and time, together with constants which characterize the soil and soil solution. This, in fact, has been the primary object of numerous investigations.

If we can by the methods of mechanics arrive at a solution of this problem for the ideal case, we shall thus provide an avenue leading to an approximate solution of the more difficult problem offered by actual soils whose individual particles are not fixed in position and whose soil solution is not a simple substance.

As is customary and essential in the analytical treatment of phenomena depending upon quantities which vary with space and time, we seek to specify the facts with respect to an element so small that average conditions from point to point within the element are sufficiently alike that the differences may be neglected. In the present instance we may therefore fix our attention upon a small cubical element of the liquid (fig. 1) at any selected region of the soil space, and, if we successfully describe its position and its motion in terms of known quantities and known laws in a comparatively simple way, well known methods of mathematics will in all probability point the way to a final solution.

The forces acting upon such an element of liquid may be divided into two kinds, viz., those which are independent of adjacent surrounding liquid and those which are due to the presence of adjacent liquid particles. The only force of the first type is the force of gravity, which is constant in direction and magnitude and is proportional to the mass of the element. Of the latter there are three, viz., pressure, cohesion, and friction, the last-named depending upon the relative velocity of the element. Cohesion may be regarded as a negative pressure (or tension) and if we so regard it there will remain but two forces of the second kind. We may therefore say that for the chosen element there exists a force acting vertically downward proportional to the mass, a pressure on each of the six sides, and a frictional drag due to the relative slipping of the element, which may be zero for any or all of the six sides, depending upon the relative velocity at each side. As stated, the force of gravity is constant for each unit of mass of the liquid regardless of time and position. Each of the others, however, will differ in general from point to point in the liquid and at each point may change with the time, so that the

specification of each will require, in addition to the characteristic constants of the soil and liquid, coördinates of space and time.

It should be noted that this method of describing the acting forces in no way depends upon the particular location of the element of volume and is therefore a general statement which applies to each of the various elements throughout the entire region with which we are concerned. There remains, then, the real problem of specifying just how these forces depend upon space and time, or, in other words, the determination of the functional relation between such forces and the coördinates mentioned.

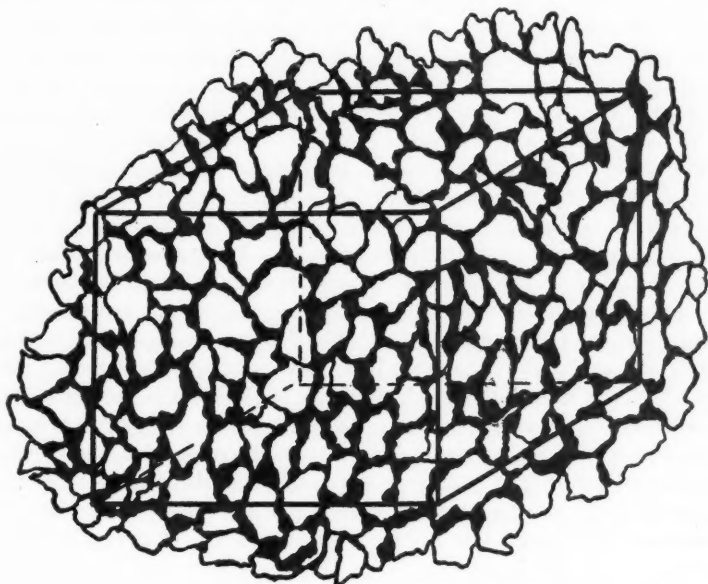


FIG. 1. DIAGRAM OF CUBICAL ELEMENT OF SOIL

Let us locate the volume element by specifying its distances,  $x$ ,  $y$  and  $z$ , measured from each of three perpendicular intersecting planes fixed in the soil. As stated, each such element should be sufficiently small that the conditions of pressure, moisture density, etc., are practically constant throughout the element but sufficiently large to include a representative mass of soil aggregate. It should be borne in mind that within the element discontinuities will arise as we pass from point to point, and in making use of this method of analysis it must be remembered that average conditions particularly concern us. The average pressure, whether it arises from the weight of superimposed liquid or from the pressure of a near-by curved surface, will in general be different for the various elements.

For bodies moving in response to conservative forces the resultant of the effective forces is a measure of their acceleration in the direction of the resultant. Where friction comes into play, however, this is not true but a limiting velocity is soon reached when the frictional force becomes equal and opposite to the resultant of the impressed forces. For small velocities of such magnitude as will be encountered in the soil, this frictional force is directly proportional to the velocity. If, for example, water is forced through a small pipe of regular or irregular section, including the pores of a homogeneous soil, the mean velocity is found from theory (8) and experiment (9) to vary directly as the pressure gradient<sup>2</sup> (6) with a proportionality factor which involves the shape and size of the tube. Where the soil is unsaturated and movement takes place in response to capillary forces, it is evident that the degree of saturation may become an additional factor, but in the absence of direct evidence that this has an appreciable effect upon the inherent moisture conductivity, we may *temporarily* ignore the moisture concentration.

The statement of this hypothesis in mathematical language will furnish a starting place for the development of the problem. Since, as stated, the force of gravity must be taken into account as well as the pressure, it becomes necessary to include its effect in the equation. The potential gradient is a force which is proportional to the mass, and, as may readily be shown, the pressure gradient is dimensionally a force per unit volume, and in order to bring these two forces together a potential function  $\Phi$ , depending upon the coordinates  $x$ ,  $y$ ,  $z$  and  $t$ , has been introduced as a measure of the potential energy per unit mass of the liquid. We may think of this as the sum of three independent terms, viz.,  $\pi$ ,  $\psi$ , and  $\varphi$ , the first being the energy due to hydrostatic pressure, the second the energy due to capillary pressure, and the third the energy due to gravity. Since the negative gradient of this potential becomes a force per unit mass, it is evident that the density  $\rho$  must be introduced as a factor, and in this way we arrive at equation (1), as may be readily shown.

Without attempting to become familiar with the meaning of the mathematical symbolism involved, the reader should note that this equation is a statement of the hypothesis, viz., that the mean velocity of any given portion of liquid through the soil is proportional to the pressure gradient, or in equivalent language, to the product of the amount of moisture in unit volume at the point in question and the rate of change of the potential energy per unit mass characteristic of such point as we move from point to point in the given region.

It should be pointed out here again also, that while the velocity of the element of liquid may ultimately depend upon a large number of factors such as

<sup>2</sup> For exceptions the experimental work of King as cited below is of interest.

By the term *gradient* as applied to any such quantity as pressure, potential, temperature, density, etc., we mean the magnitude of the change of such quantity as we move from point to point in the direction of greatest change.

the surface tension of the liquid, the coefficient of viscosity of the liquid, the porosity of the soil, the size and shape of the individual grains, the temperature, the barometric pressure, and so on, yet the effect of each will be made manifest through one or the other of the three quantities,  $K$ ,  $\rho$ , and  $\Phi$ .

It is evident that whatever may be the character of the motion, the rate of accumulation (positive or negative) of liquid within a given region is determined uniquely by the velocities of the numerous individual particles located on the boundary of such region, or, in other words, the increase or decrease of moisture must be accounted for by the flow through the boundary of such region. The mathematical expression of this fact is in the form of another equation (2), the equation of continuity. And, if we multiply equation (1) by the moisture density  $\rho$  and substitute in equation (2) we obtain finally equation (3), or, the equivalent form, equation (4), a relation which expresses quantitatively and briefly our hypothesis combined with the equation of continuity.

Furthermore, since the density of moisture at any point depends upon the original density, the rate of accumulation, and the time, it would seem only logical to expect that a knowledge of these quantities and a knowledge of limiting conditions, together with methods of calculation, should be sufficient for the determination of the moisture density at any given region at any given time, which is the end sought in the investigation. The application of the equation to experimental facts is therefore very largely a matter of mathematical technique and, as previously stated, it is not expected that the non-mathematical reader will be able to follow the steps in detail. In the mathematical development, however, a number of simple expressions have been deduced as a result of the application of the general equation to certain kinds of soil-moisture phenomena, and in some cases experimental results are shown in graphical form, indicating in general the confidence that may be attached to the validity of our hypotheses.

In equation (4) there appears a factor  $p$ , the capillary pressure, which we are unable to measure directly, and an attempt has been made to evaluate this in terms of the moisture density. In a previous article (1) one of the authors has made use of the tentative relation,

$$\frac{\partial p}{\partial x} = \frac{k_2}{\rho^{\frac{2}{3}}} \frac{\partial \rho}{\partial x} \text{ or } \nabla p = \frac{k_2}{\rho^{\frac{2}{3}}} \nabla \rho \quad (a)$$

and in a subsequent article (4) it has been pointed out that there is some experimental evidence indicating that the capillary potential<sup>3</sup>  $\psi$  is a linear function of the reciprocal of the moisture density  $\rho$  over a considerable range for a large number of soils, thus:

$$\Psi = \frac{c}{\rho} + b \quad (b)$$

<sup>3</sup> The symbol  $\varphi$  has been used previously (4) for this potential. It is perhaps better, however, to reserve  $\varphi$  for the gravitational potential.

and, since, as previously stated, the potential gradient and the pressure gradient differ by a factor of the dimensions of  $\rho$ , it follows that the relation must be of the form,

$$\nabla p = \frac{c}{\rho} \nabla \rho \quad (c)^4$$

where  $c$  is a constant satisfying the relation (b). We make use of equation (c), however, subject to any modification that may be found necessary in equation (b).

The constants in the equations which have been plotted in the second section were determined arbitrarily. They involve not only the boundary conditions but also constants which are characteristic of the soil and soil solution. It is not our purpose in this brief discussion to consider in detail the magnitude and significance of these characteristic constants. In the notation, however, an attempt has been made to preserve the identity of Slichter's transmission constant, designated by  $K$ ; the slope parameter of the Briggs potential function, designated by  $c$ ; the capillary transmission constant  $k$ ; and the lentocapillarity constant designated by the small Greek letter  $\kappa$ .

## II. MATHEMATICAL DEVELOPMENT OF THE PROBLEM TOGETHER WITH EXPERIMENTAL DATA IN GRAPHICAL FORM

As stated in the introduction, we make the original assumption that the mean velocity of the water through the soil is proportional to the pressure gradient, or more generally, to the force per unit volume, and we therefore write,

$$v = K\rho\nabla\Phi \quad (1)$$

where

- $v$  = mean velocity at a point in the soil
- $K$  = a proportionality constant
- $\rho$  = moisture density at the point
- $\Phi$  = sum of three potentials,  $\pi$ ,  $\Psi$  and  $\varphi$
- $\pi$  = potential due to hydrostatic pressure
- $\Psi$  = potential due to capillary pressure
- $\varphi$  = potential due to gravity

<sup>4</sup> Since this article was submitted for publication some unpublished experimental work of Mr. Thomas of the Agronomy Department has come to our attention indicating that the vapor pressure is approximately an hyperbolic function of the moisture content. By a well known method it may be shown that the capillary pressure  $p$  is related to the vapor pressure  $\pi$  as follows:  $\pi = p - RT \log \frac{p}{p_0}$  and a simple algebraic substitution leads to a converging series which for finite values of the vapor pressure, differing only slightly from the average vapor pressure of water, is identical in form with equation (b).

$$\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z} \quad (\text{a mathematical operator})$$

$$\nabla \Phi = \frac{1}{\rho} \nabla (P + p) + \nabla \varphi$$

$P$  = hydrostatic pressure

$p$  = capillary pressure

The equation of continuity must be everywhere satisfied, and we therefore write,

$$\frac{\partial \rho}{\partial t} = - \nabla (\rho v) \quad (2)$$

Multiplying (1) by  $\rho$  and substituting in (2), we obtain,

$$\frac{\partial \rho}{\partial t} = - K \nabla (\rho^2 \nabla \Phi) \quad (3)$$

or the equivalent form (remembering that  $\nabla^2 \varphi = 0$ )

$$\frac{\partial \rho}{\partial t} = - K \{ \rho \nabla^2 (P + p) + \nabla \rho [\nabla (P + p) + 2 \rho \Delta \varphi] \} \quad (4)$$

The product in the second member is scalar.

The following important cases may be considered in the solution of equation (4).

(1) When  $P$  is finite,  $p = 0$ ,  $\nabla p = 0$ ,  $\frac{\partial \rho}{\partial t} = 0$ . This case is realized when the pore space of the soil is full, and we have,

$$\nabla^2 P = 0 \quad (I)$$

Detailed consideration of this case has been given by Slichter (9) and will not be discussed here.

(2) When  $p$  is finite,  $P = 0$ . This is the most common condition met with in irrigation practice. For this case equation (4) reduces to,

$$\frac{\partial \rho}{\partial t} = - K \{ \rho \nabla^2 p + (\nabla p)^2 + 2 \rho \nabla \varphi \nabla \rho \} \quad (II)$$

For reasons discussed elsewhere in this article, we make the tentative assumption that

$$\Psi = \frac{c}{\rho} + b$$

which leads to

$$\nabla p = \frac{c}{\rho} \nabla \rho$$

and if we make this substitution for  $\nabla p$  in (II), we obtain,

$$\frac{\partial \rho}{\partial t} = -Kc \left\{ \nabla^2 \rho + \frac{2\rho}{c} \nabla \varphi \nabla \rho \right\} \quad (\text{II}')$$

This becomes for a steady state,

$$\nabla^2 \rho + \frac{2\rho}{c} \nabla \varphi \nabla \rho = 0 \quad (\text{II}'')$$

Integrated for vertical flow and so choosing the coördinates that  $\frac{\partial \rho}{\partial z}$  is negative, this becomes,

$$\rho = A \tan (B-Cz) \quad (\text{a})$$

where  $A$ ,  $B$ , and  $C$  are constants involving the characteristic constants of the soil and soil solution, the gravitational acceleration constant  $g$ , together with the boundary conditions; and  $z$  is the distance measured vertically from an appropriate origin.

In the special case where  $\rho = \rho_0$  when  $z = 0$ , and  $\frac{\partial \rho}{\partial z} = 0$  when  $z = \infty$ , we obtain,

$$\rho \left( z - \frac{c}{\rho_0 g} \right) = - \frac{c}{g} \quad (\text{b})$$

In figure 2 are plotted experimental curves showing the distribution of moisture with height in a series of soil tubes of about 100 inches in height, which had been saturated with water and allowed to stand for a long time, various types of soil being represented. These curves were taken from data given by King (7). Superimposed are plotted with a broken line representative curves with arbitrary constants for families (a) and (b). King states that the sands continued to drip for a period of about two and a half years and it is possible that they had not attained a condition of equilibrium when the analyses were made. It is of interest to note also that one of the authors (10) found an equation of the family (b) satisfied approximately for Greenville soils in 24 to 48 hours after irrigation, this condition representing, however, a condition of steady motion, the moisture density diminishing with the depth. As pointed out in a previous publication (2) the moisture density  $\rho$  should be interpreted as that in excess of what has been designated as the lento-capillarity point. Another alternative would be to introduce this additional characteristic constant  $\kappa$ . Equation (b), for example, would thus become,

$$(\rho - \kappa) \left( z - \frac{c}{\rho_0 g} \right) = - \frac{c}{g} \quad (\text{b}')$$

The lento-capillarity parameter  $\kappa$  is a measure of the ordinates of the respective asymptotes of the curves.

(3) When  $p$  is finite,  $P = 0$ , and  $\nabla\phi\nabla\rho = 0$ . This case is realized where the water flows horizontally under the influence of capillary pressure. The product  $\nabla\phi\nabla\rho$  vanishes in this case, since it is the scalar product of perpendicular vectors, and equation (4) reduces to,

$$\frac{\partial\rho}{\partial t} = -Kc\nabla^2\rho \quad (\text{III})$$

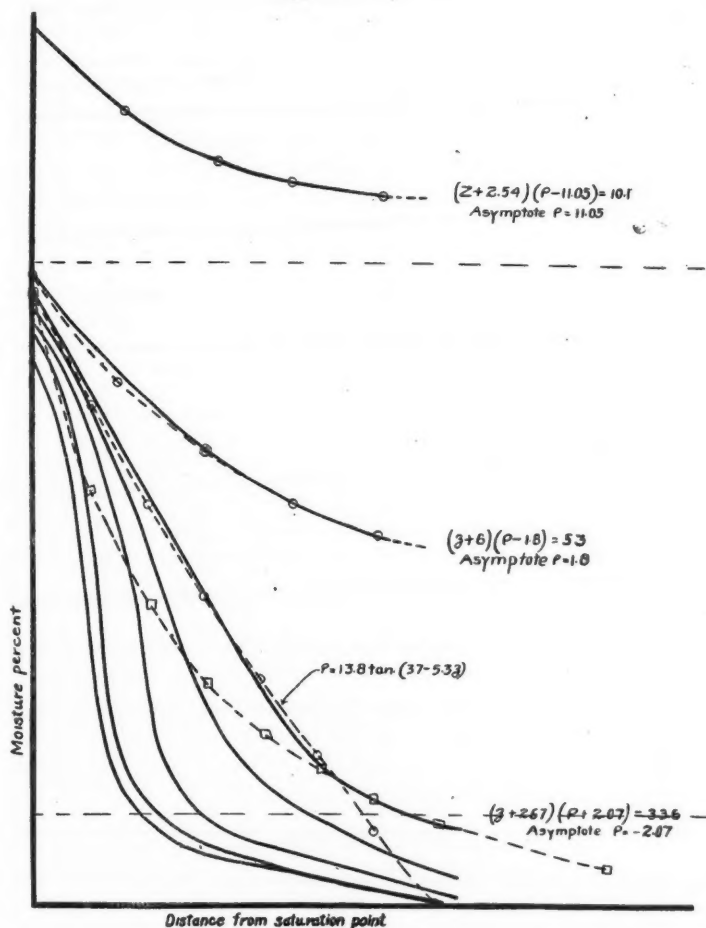


FIG. 2. THE DISTRIBUTION OF MOISTURE WITH DISTANCE FROM WET END (BOTTOM OF TUBE); PLOTTED FROM DATA GIVEN BY KING

This will be recognized as the well known heat equation, with a diffusion constant  $Kc$  ( $=k$ ), i.e., the product of Slichter's transmission constant  $K$  and the slope parameter  $c$  in the Briggs potential equation. This will differ

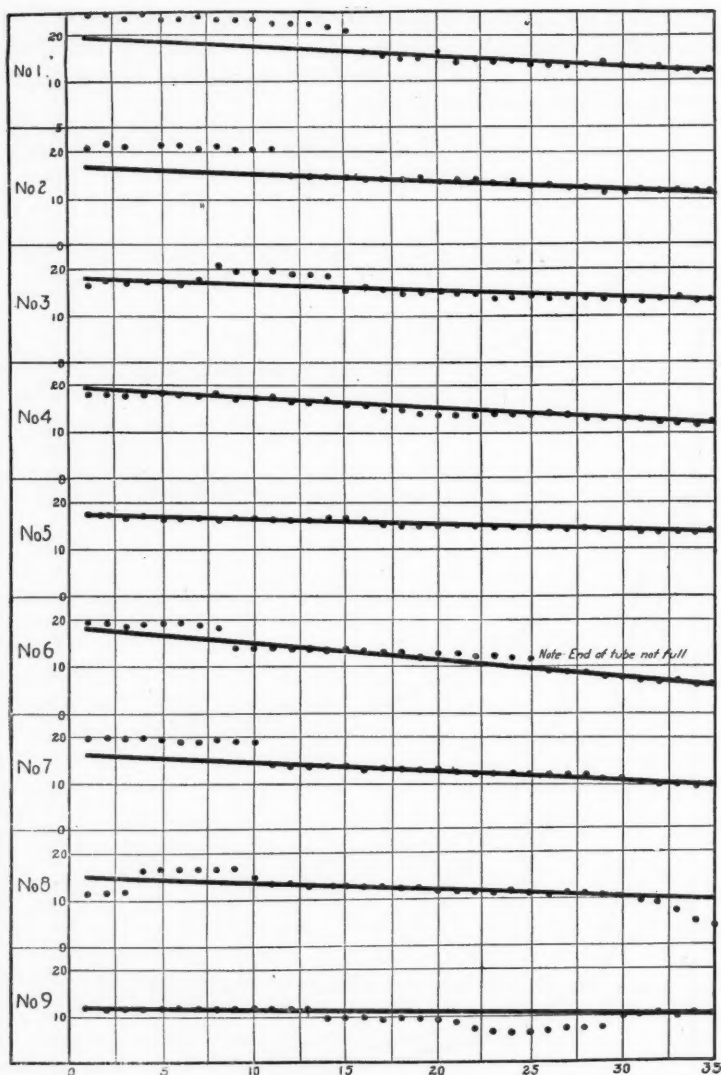


FIG. 3. THE DISTRIBUTION OF MOISTURE WITH DISTANCE FROM WET END FOR A SERIES OF HORIZONTAL TUBES AFTER THE MOISTURE HAD BEEN ALLOWED TO MOVE LATERALLY ABOUT 24 INCHES FROM ONE END WHICH WAS KEPT SATURATED

After reaching this point the source of supply was discontinued for about four months before analyses were made. The ordinate is given as per cent on the dry basis and the abscissa as inches from the wet end.

from the capillary transmission constant as previously defined and measured (3) by a factor ranging from about 1.3 to 1.7.

When solved for a steady state, we have,

$$\nabla^2 \rho = 0 \quad (\text{III}')$$

and for one dimensional flow,

$$\rho = Ax + B \quad (\text{a})^5$$

In figure 3 are plotted nine curves representing the moisture distribution in a series of nine horizontal tubes 100 cm. long which had been filled with dry soil and irrigated by capillarity from one end. After a period of 7 days when the water had traversed about three-fourths the length of the tubes the source of water was discontinued. The tubes were allowed to stand for about 4 months and moisture determinations were made, one tube being analyzed each week for 9 weeks. These curves are shown here to illustrate the approximately linear distribution of the moisture in the tubes. It is evident, however,

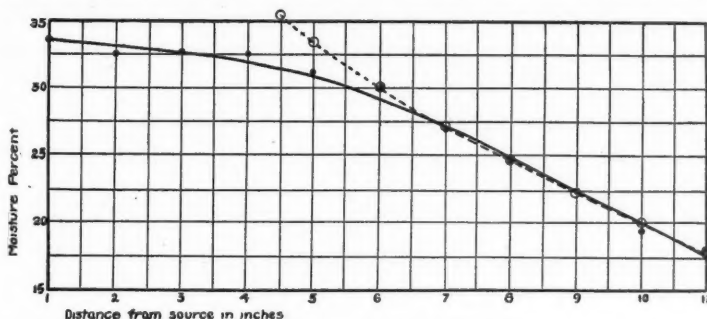


FIG. 4. DISTRIBUTION OF MOISTURE FOR APPROXIMATELY STEADY STATE FOR RADIAL FLOW

that an insufficient range of time and distance is represented completely to verify equation (a). Since also there was a slow readjustment in process the condition was only approximately steady.

For the case of radial flow in two dimensions, equation (III) becomes when integrated for a steady state,

$$\rho = C \log (x + 1) + \rho_0 \quad (\text{b})$$

and in figure 4 are plotted the results of a preliminary test of the moisture distribution in the soil which had been irrigated from a central irrigation ditch, and the water allowed to move horizontally in all directions for a period of about 160 hours before moisture determinations were made. The soil was covered with a piece of cardboard to minimize the effect of evaporation. It can only be assumed, however, that this represents approximately a steady

<sup>5</sup> If equation (a), p. 219, be used in place of (c) p. 220, this equation becomes  $\rho = (Ax + B)^{\frac{1}{2}}$ , as shown in a former publication (1).

condition. The theoretical curve is shown as in previous cases. It is to be expected that the theoretical curve will represent the moisture distribution only beyond the point of complete saturation.

(4) When  $p = 0$ ,  $P = 0$ ,  $\nabla\varphi = -g$ , with no constraints except frictional resistance which is proportional to the length of the water column, which in turn is proportional to the mass. This case would be realized were it possible to allow a column of water completely filling the pore space of the soil to drop under the influence of gravity without developing surface energy at either end of the column. In this case  $\frac{\partial\rho}{\partial t} = 0$ ,  $\rho$  is constant, and all the terms in the right-hand member of equation (4) are zero. Equation (1), however, becomes,

$$v = K\rho\nabla\varphi = -K\rho g = \text{constant} \quad (\text{IV})$$

It is of course impossible fully to realize this case in practice (A, fig. 10), since  $\nabla p = \frac{c}{\rho}\nabla\rho$  is finite at the water front, although it may become negligible in comparison with  $\rho\nabla\varphi$  in a short time. If we consider the case of vertical flow, however, and write,

$$\begin{aligned} \rho v &= K\rho\nabla p + K\rho^2\nabla\varphi \\ &= Kc\nabla\rho + K\rho^2\nabla\varphi \\ &= -K\rho^2g + Kc\frac{\partial\rho}{\partial z} \quad (\text{since } \nabla\varphi = -g) \end{aligned}$$

and consider the value of  $\rho v$  at the water front, we have

$$\rho_a \frac{\partial a}{\partial t} = -K\rho_a^2g + Kc\frac{\partial\rho}{\partial z} \quad (z=a)$$

and if we substitute

$$\rho = \rho_0 + \alpha e^{-\beta t}$$

(where  $\rho_0$  and  $\alpha$  are independent of  $t$ )

which may be made to satisfy (III), and (II) to a first approximation, we may write,

$$\frac{\partial\rho}{\partial z} = -Ae^{-\beta t}$$

if  $\rho_0$  is also independent of  $z$  and  $A \left( = \frac{\partial\alpha}{\partial z} \right)$  is independent of  $t$ . And from this we obtain,

$$\frac{\partial a}{\partial t} = -K\rho_a g + \frac{Kc}{\rho_a} Ae^{-\beta t}$$

and

$$a = c_1 t + c_2 (1 - e^{-\beta t}) \quad (\text{approximately}) \quad (\text{a})$$

As will be noted from the manner of performing the integration, a positive correction term should be added for small values of  $t$ .

In figure 5 are given in graphical form the results of an experiment performed in the laboratory illustrating this case. At the top of a column of sand originally air-dry about 3 meters high and 3.5 cm. in diameter, was fed a stream of water just sufficient to keep the surface covered completely, and the distance of the water front from the surface was recorded with the time and the curves plotted as shown. The lower curve represents a coarse sand of 0.06 cm. mean diameter, the next a medium sand of 0.04 cm. diameter, and the top a fine sand of 0.03 cm. diameter. The experimental points fell almost exactly on the curve and are not shown, but the theoretical points as calculated from equation (a) are shown with a circle.

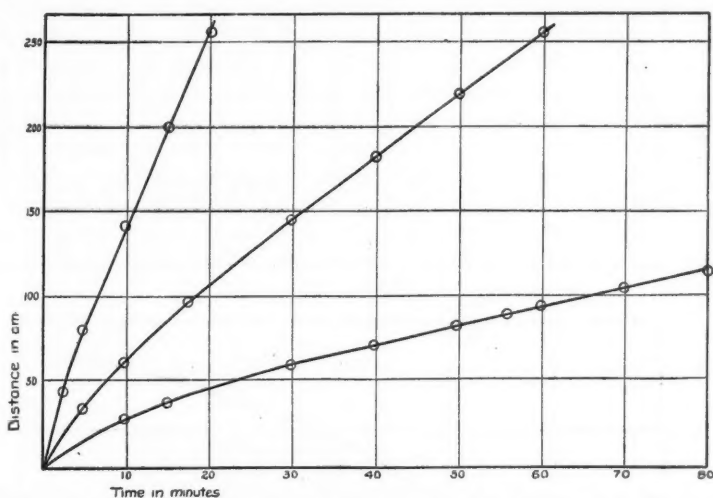


FIG. 5. THE DOWNWARD MOVEMENT OF A COLUMN OF WATER THROUGH SAND PARTICLES OF VARIOUS SIZE

The surface of the sand was kept saturated in an attempt to approximate complete saturation throughout the column from the source to the water front.

It is evident that the locus of (a) will range from a straight line to an exponential curve with asymptote  $c_2$ , depending upon the ratio of  $c_1$  to  $c_2$ , this ratio increasing as the soil changes in texture from clays to sands. For horizontal capillary flow, it is evident that  $c_1 = 0$ , and for vertical flow with fine-textured soils  $c_1$  may perhaps be of negligible magnitude in comparison with  $c_2$ , and equation (a) becomes,

$$a = c_2 (1 - e^{-\beta t}) \quad (b)$$

In figure 6 is shown the graph of water-front, distance, and time data obtained in the laboratory from a rectangular box 6 by 9 cm. in cross-sectional area, one end of which was bent downward and kept permanently in contact with

free water maintained at a constant height about 10 cm. below the center of the box. The broken line represents a typical curve of the family (b), whereas

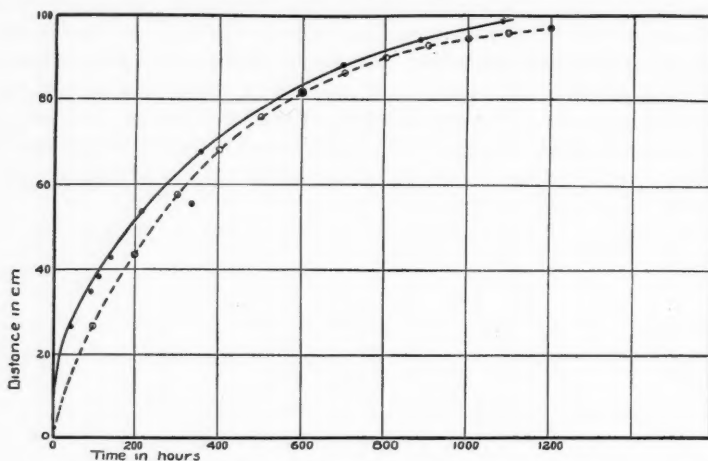


FIG. 6. THE DISTANCE OF THE WATER FRONT FROM THE SOURCE OF SUPPLY AS A FUNCTION OF THE TIME

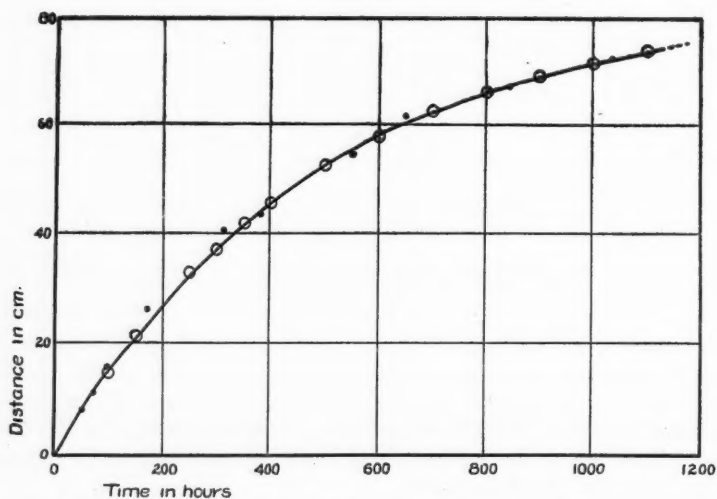


FIG. 7. A PART OF THE DATA OF FIGURE 6 WITH THE ORIGIN OF COÖRDINATES SHIFTED ALONG THE CURVE

the full line with black dots represents the experimental data. It is evident, however, that equation (b) would hold only from the end of the saturated column (fig. 10), and while the experimental data were not conclusive on this

point, it is to be expected that the end of the column nearest the source of supply should become completely saturated for a limited distance. In figure 7 is shown a part of the data of figure 6 with the origin shifted along the curve an arbitrary short distance, and it may be seen that the theoretical points fall almost precisely on the transformed curve.

In figure 8 are plotted curves representing the average values for similar distance-time data for a series of duplicate vertical tubes where the moisture was allowed to move up in the one case and down in the other from soils of varying moisture content into dry soil (B, fig. 10). The data for these curves were obtained from the published work of Harris and Turpin (5). The constants of equation (b) were determined for each of the several curves of the series and the theoretical curves are shown as in the other cases. It is evident here that neglecting the correction term above mentioned gives rise to a considerable difference in theoretical and experimental curves for small values of  $t$ . It should also be observed that the asymptote will change slowly with the time ultimately becoming infinite, since the equation was integrated assuming that slowly varying coefficients were constant.

Another case of interest may be noted. If we consider the amount of moisture  $Q$  in a given section of soil (C, fig. 10) as a function of the time, we may write for the quantity of moisture in a section of unit area and length  $a$ ,

$$Q = \int_0^a \rho dx, \quad \frac{\partial Q}{\partial t} = \int_0^a \frac{\partial \rho}{\partial t} dx = \int_0^a -Kc \left( \frac{\partial^2 \rho}{\partial x^2} - \frac{2\rho}{c} g \frac{\partial \rho}{\partial x} \right) dx$$

$$= -K \left\{ c \left[ \frac{\partial \rho}{\partial x} \right]_{x=a} - \frac{\partial \rho}{\partial x} \right|_{x=0} - g[\rho_a^2 - \rho_0^2] \right\}$$

If we assume that

$$\rho = \rho_0 + \alpha e^{-\beta t}$$

where  $\rho_0$  is independent of  $x$  and  $t$  and  $\alpha$  is independent of  $t$ , and make this substitution, we obtain

$$\frac{\partial Q}{\partial t} = -K \{ c e^{-\beta t} (A_a - A_0) - 2 g \rho_0 e^{-\beta t} (\alpha_a - \alpha_0) - g e^{-2\beta t} (\alpha_a^2 - \alpha_0^2) \}$$

$$= -K e^{-\beta t} \{ c (A_a - A_0) - 2 g \rho_0 (\alpha_a - \alpha_0) - g (\alpha_a^2 - \alpha_0^2) e^{-\beta t} \}$$

and

$$Q = \kappa' + L e^{-\beta t} + M e^{-2\beta t} \quad (V)$$

where  $\kappa'$ ,  $L$ , and  $M$  are constants. The asymptote  $\kappa'$  is the lento-capillarity constant as measured by one of the authors (10). It is evident, however, that it is in reality a measure of the equilibrium moisture density immediately below the stratum affected by evaporation, which may be far above the amount of the residual "solid" film adhering to the surface of the soil grains. Strictly speaking, the term should designate this residual film. The meaning of  $L$  and  $M$  will no doubt be evident from the integration.

In figure 9 are plotted the mean values of the water content in the first 6 feet of a field plot at the Greenville Experiment Farm as a function of the

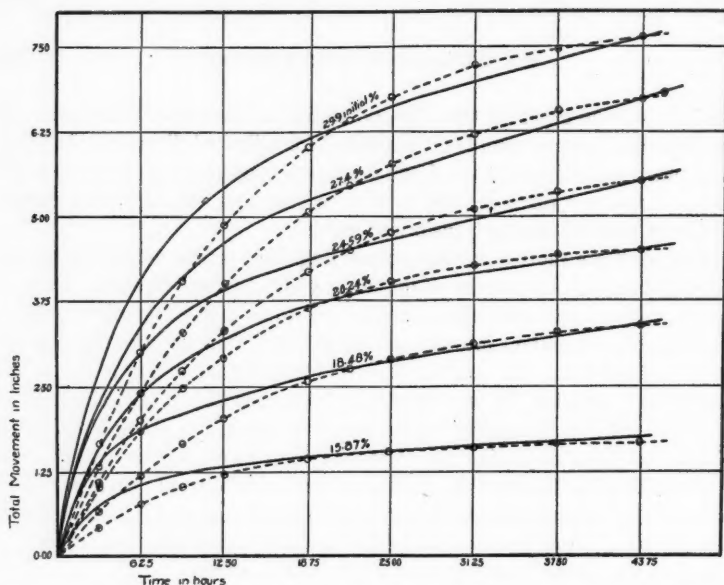


FIG. 8. THE DISTANCE OF WATER FRONT AND TIME DATA WHERE WATER WAS ALLOWED TO MOVE INTO DRY SOIL FROM MOIST SOIL OF VARYING MOISTURE CONTENT

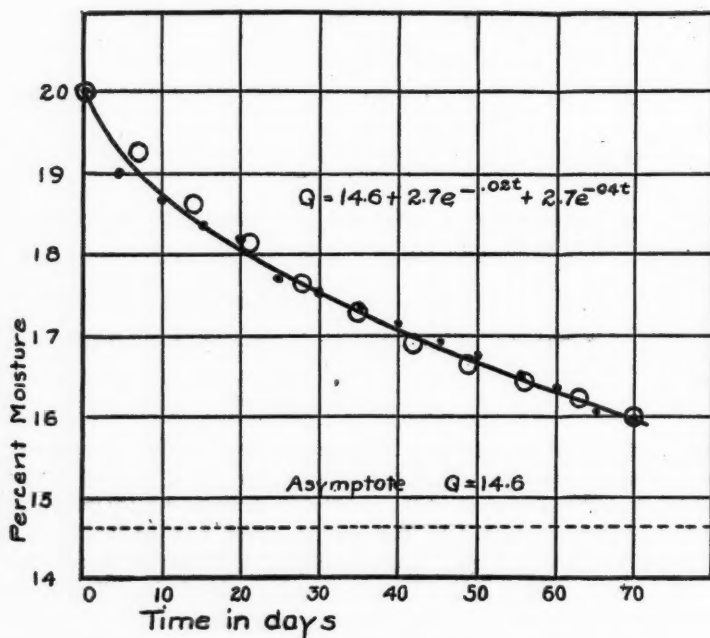


FIG. 9. THE DOWNWARD MOVEMENT OF MOISTURE IN A FIELD SOIL

The ordinate represents the average moisture content in the first 6 feet of soil expressed as per cent on the dry basis, the abscissa represents time in days from the time of maximum moisture content.

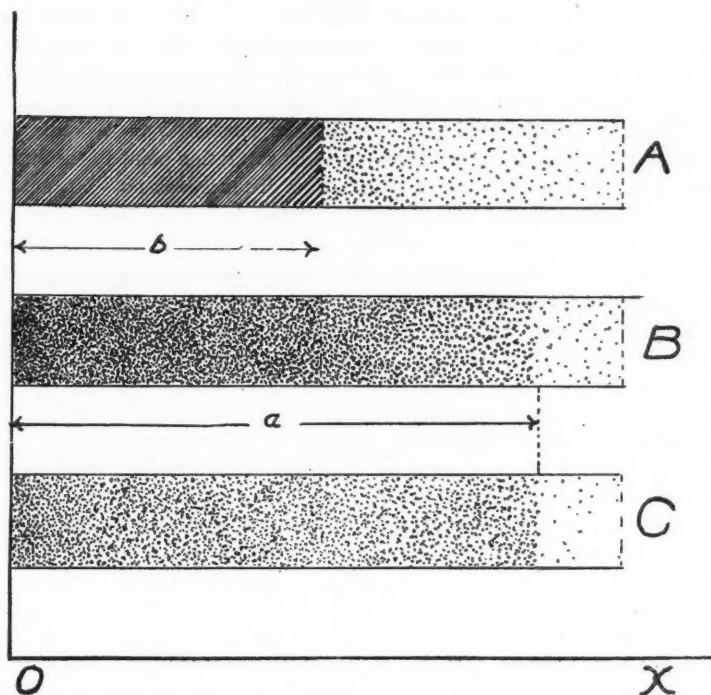


FIG. 10. DIAGRAM OF SOIL COLUMNS OF VARYING MOISTURE CONTENT

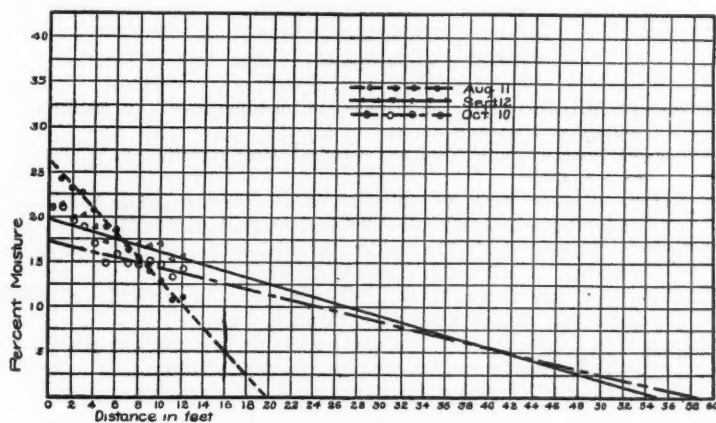


FIG. 11. THE EXTRAPOLATED CURVES APPROXIMATING THE MOISTURE DISTRIBUTION IN A HORIZONTAL BOX WHERE MOISTURE WAS ALLOWED TO MOVE HORIZONTALLY. Three curves are shown corresponding to different dates over a 70-day period.

time after a long continued thorough sprinkling of the plots. The theoretical values derived from (V) are indicated as in the previous cases. It is apparent also in this case that regardless of its theoretical significance equation (V) is in harmony with the experimental facts.

The constant  $\beta$  is the product of the diffusion constant  $k$  ( $= Kc$ ) and the reciprocal of the distance from the extrapolated saturation point to the extrapolated point of zero moisture content. This distance was not constant in this experiment but ranged from about 20 to 60 feet during the 70-day interval, as may be seen from the slope curves shown in figure 11 for the extremes of this time interval. If we use 40 feet as an approximate average, we obtain, after reducing to c. g. s. units,  $k = -2.7 \times 10^{-3}$ , which is consistent with values previously determined (3).

### III. CONCLUSION

Two assumptions have been made in the development and integration of a general equation for the movement of moisture through an *ideal* soil, viz.,

(a) The inherent moisture conductivity in such a soil is independent of the moisture content.

(b) The capillary potential is a linear function of the reciprocal of the moisture content.

The general equation has been solved for various special cases and experimental results obtained from ordinary soils have been shown supporting the general theory.

It is not held, however, that the results are wholly conclusive. Departures from the general equation and its integrated forms that may arise in future investigations may be traced to one or the other of the two assumptions named. The theoretical material is presented, however, primarily as a working hypothesis, with the hope that those who may be interested will assist in the perfection of the methods of investigation of these and correlated problems.

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## SOME STUDIES ON THE RATE OF FORMATION OF SOLUBLE SUBSTANCES IN SEVERAL ORGANIC SOILS

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### INTRODUCTION

Researches concerning the rate of formation of soluble salts in a great many mineral soils have been made, but little is known of the behavior of organic soils under similar conditions. It is the purpose of this paper to present the results of a preliminary study of such activities in seven organic soils. The work includes the following considerations:

A. (1) Relative solubility (solubility is taken to mean the power of soil to form soluble substances) at different temperatures. (2) Relative solubility under different moisture conditions.

B. (1) Relative solubility of different depths of the soil section under optimum moisture conditions.

### GENERAL PROCEDURE

The freezing-point method for the determination of soluble material in the soil solution, as devised by Bouyoucos (1) was employed as the means of studying the changes in concentration. The samples were always frozen while saturated with water. Freezings were made in duplicate, but in some cases difficulties were encountered in obtaining concordant results. The samples were aerated regularly while in storage. A constant temperature of 25°C. was maintained in a large chamber equipped with heating coils and a thermostat, while a temperature of 7°C. was obtained by means of a ventilated cold room used for the cold storage of fruits.

The soils used in the work discussed under section A of this paper were surface samples, while those described in section B were procured by digging a pit having one perpendicular wall from which blocks of soil could be removed at suitable depths.

### DESCRIPTION OF SOILS

1. *Mt. Hope*. A very low lying deposit formed largely from woody accumulations, but having a well decomposed surface of about 8 inches in depth, which was covered with blue-grass sod. Drainage was found to be rather poor, and the lower sections were mostly partially decayed trees and stumps.

At about 40 inches a shallow marl deposit was found. The water-table ordinarily occurs about 12 inches from the surface.

2. *Shaw*. This soil was drained artificially about 15 months previous to sampling and was found to be quite peaty after the upper 5 or 6 inches of friable material had been removed. Weeds and some willows constituted the only vegetation. The deposit seemed to have been formed by the accumulation of mosses and sedges, as many leaf forms were distinguishable in the lower levels. The deposit is a deep one, probably exceeding 10 feet in thickness, and the water-table generally stands at approximately 24 inches from the surface.

3. *Farm Lane*. This is a rather shallow deposit, which has been drained and under cultivation for about 25 years. It has about 12 inches of well oxidized material on top, which is quite sticky, but is rather peaty underneath. It was undoubtedly formed from mosses and sedges. The water-table is usually at a depth of 30 inches. At the time of sampling there was an excellent stand of clover and timothy upon it.

4. *Town Line*. A deposit, reaching only about 3 feet in depth, of material well decomposed nearly to the bottom. The drainage is excellent and a meadow sod exists on the soil. The material resembles the Farm Lane sample as to origin.

5. *Chandler*. This body of soil consists of many thousand acres, for the most part well drained. The deposit was under water, however, until about three years previous to the time the samples were taken. It is covered with a blue-grass sod, many willows and some small poplars. The surface is decomposed to a depth of about 8 inches, gradually changing to a very fibrous peat, in which coarse stems of plants and some tree stumps are noticeable. The water-table at the point of sampling was never encountered at the depth of 36 inches.

6. *Plots*. The drainage being poor, the soil is a very fibrous and coarse peat from the surface downward, and supports a scanty growth of poplar and willow, with occasionally patches of blue-grass sod. In some parts of the soil section, poplar roots and other woody substances are found. Decomposition has scarcely begun and water stands at the surface a large portion of each year.

7. *Interurban*. Taken from the roadside near a small swamp stream. Elms flourish upon it as well as some small bushes. The surface 8 inches is quite granular, changing quickly to a very tough layer nearly 10 inches thick which resembles lignite. Water stands at this point. Below this a peaty substance is found and at a depth of about 3 feet a blue, mottled clay occurs. The intractable layer, when dry, becomes so hard, that it is necessary to grind it before it can be passed through a screen. This soil presents an unusual soil section.

## EXPERIMENTAL

*A. The effect of temperature and moisture upon the formation of soluble material*

About 400 gm. of each air-dry soil were placed in large funnels, and leached with 100-cc. portions of distilled water until 700-cc. had run through each filter. This treatment was sufficient to reduce the concentration of the soil solution almost to zero. As each 100-cc. portion of the leachings was collected the freezing-point lowering was determined. The data in table 1 from two of the samples shows the amount of material in each portion.

Thus, at first there is an appreciable quantity of soluble material washed out, but the amount gradually decreases, until a nearly constant loss occurs. The amount remaining in solution in the soils may then be considered to be almost negligible.

TABLE 1  
*The freezing-point lowerings and parts per million found in the leachings*  
0.003°C. Depression = 100 p.p.m. (1).

	SAMPLE 1		SAMPLE 2	
	Freezing-point depression	Parts per million.	Freezing-point depression	Parts per million.
	°C.		°C.	
First 100 cc.....	0.008	266	0.012	400
Second.....	0.010	333	0.008	266
Third.....	0.006	200	0.005	166
Fourth.....	0.004	133	0.004	133
Fifth.....	0.002	66	0.004	133
Sixth.....	0.003	100	0.003	100
Seventh.....	0.002	66	0.002	66

After drainage had ceased the soils were placed in pans and thoroughly mixed, and six freezing tubes of each saturated soil prepared. The remainder of the soil was allowed to dry in air to an optimum moisture condition. Three of the freezing tubes were stored at 25°C. while the other three were kept at 7°C. The freezing-point depression of each soil was obtained at this point as the initial concentration. The contents of the tubes were frozen after 13, 25, 38 and 50 days had elapsed.

The data obtained are summarized in tables 2 and 3 and graphically shown for soils 1 and 5 in figures 1 and 2. The data in these tables show that in all the soils studied at both temperatures there is a rather rapid rise in the concentration of the solutions for a certain time, after which a decrease occurs. The time required to reach the maximum depression varies with each soil. Also, for any one soil, different temperatures cause variations in the time. Thus soil 1 at 25°C. reached its greatest depression after about 13 days, while at 7°C. it required 38 days to produce nearly the same concentration. This soil, then, required nearly three times as long to attain the crest when kept

TABLE 2  
Freezing-point lowerings of soils kept under saturated moisture conditions and at a temperature of 25°C.

SAMPLE	FREEZING-POINT DEPRESSIONS				
	Original	13 days	25 days	38 days	50 days
	°C.	°C.	°C.	°C.	°C.
1	0.002	0.050	0.026	0.025	0.015
	0.001	0.053	0.024	0.022	0.017
2	0.002	0.036	0.022	0.010	0.007
	0.003	0.034	0.020	0.014	0.009
3	0.002	0.028	0.022	0.018	0.022
	0.003	0.028	0.020	0.020	0.018
4	0.002	0.038	0.022	0.034	0.033
	0.004	0.040	0.020	0.030	0.029
5	0.002	0.043	0.037	0.020	0.021
	0.002	0.047	0.036	0.024	0.022
6	0.000	0.008	0.014	0.010	0.012
	0.001	0.010	0.014	0.010	0.014
7	0.003	0.062	0.053	0.054	0.043
	0.002	0.058	0.051	0.052	0.045

TABLE 3  
Freezing-point lowerings of soils kept under saturated moisture conditions and at a temperature of 7°C.

SAMPLE	FREEZING-POINT DEPRESSIONS				
	Original	13 days	25 days	38 days	50 days
	°C.	°C.	°C.	°C.	°C.
1	0.002	0.036	0.040	0.050	0.042
	0.001	0.040	0.042	0.052	0.045
2	0.002	0.024	0.025	0.022	0.024
	0.003	0.020	0.028	0.024	0.020
3	0.002	0.018	0.018	0.010	0.014
	0.003	0.018	0.020	0.008	0.014
4	0.002	0.032	0.028	0.028	0.016
	0.004	0.028	0.030	0.026	0.014
5	0.002	0.036	0.050	0.024	0.032
	0.002	0.038	0.050	0.022	0.028
6	0.000	0.007	0.015	0.006	0.007
	0.001	0.010	0.013	0.007	0.006
7	0.003	0.042	0.052	0.027	0.028
	0.002	0.038	0.048	0.028	0.028

at the lower temperature. Again, at 25°C. soil 6 required 25 days to rise, as compared with 13 days for soil 1. Soil 6 is a very fibrous peat, and is rather slow in forming soluble material. The similarity which exists between the other five samples and no. 1 with regard to rate of action is worthy of consideration. While each gave a different depression, they were all at their highest point in 13 days. At the lower temperature, the soils vary much more, requiring from 13 days to 38 days to reach the highest concentration. In general, the lower temperature tends to retard the formation of soluble material.

McCool and Millar (2) found somewhat similar results with mineral soils, and attribute the decrease in salt content to either reabsorption, chemical change which produced less soluble materials or to biological activity. It is very probable that in organic soils, the latter is of great importance, as is also absorption. A study of this phenomenon is now in progress in this laboratory,

TABLE 4  
*Moisture content of soils at the time of the original freezing-point determination, together with the water necessary to obtain saturated conditions*

SAMPLE	MOISTURE DURING STORAGE	WATER ADDED TO EACH BOTTLE FOR FREEZING
	<i>per cent</i>	<i>cc.</i>
1	65.78	12
2	63.61	12
3	61.10	12
4	62.19	12
5	66.45	16
6	73.35	25
7	63.15	17

which seems to show that some ions steadily increase in soil solutions while others rise and then decrease in amount. Since the freezing-point method measures only the resultant solubilities, it is not improbable that as new substances are formed with different solubility products the amount of material affecting the freezing point will change constantly. So it may be shown that chemical change also plays its part in varying the salt content of soils, both in amounts and in composition.

When the samples of each soil for the preceding section had been removed the remainder was dried in air until optimum moisture was obtained. Eight sample bottles, each of 150-cc. capacity, and fitted with a stopper, were employed and 40 gm. of soil placed into each one. Also a sample was frozen at once, to provide the original readings. Four bottles of each muck were kept at 25°C. and four bottles at 7°C. After 10, 20, 40 and 60 days, respectively, one bottle of each soil from each temperature was frozen after enough distilled water had been added to make saturated moisture conditions.

These samples were frequently aired while in storage. The moisture percentages at which the soils were stored, and the amounts of distilled water per bottle necessary to obtain saturation are presented in table 4.

TABLE 5  
Freezing-point lowerings of soils kept under optimum moisture conditions and at the temperature of 25°C.

SAMPLE	FREEZING-POINT DEPRESSIONS				
	Original	10 days	20 days	40 days	60 days
	°C.	°C.	°C.	°C.	°C.
1	{ 0.003	0.024	0.050	0.033	0.035
	{ 0.001	0.021	0.048	0.032	0.032
2	{ 0.002	0.017	0.044	0.050	0.052
	{ 0.004	0.018	0.042	0.046	0.048
3	{ 0.002	0.021	0.028	0.040	0.020
	{ 0.003	0.019	0.028	0.041	0.024
4	{ 0.007	0.032	0.033	0.062	0.052
	{ 0.009	0.028	0.036	0.059	0.052
5	{ 0.006	0.024	0.060	0.072	0.060
	{ 0.005	0.026	0.056	0.068	0.062
6	{ 0.004	0.008	0.014	0.010	0.006
	{ 0.005	0.010	0.012	0.012	0.006
7	{ 0.005	0.034	0.033	0.038	0.042
	{ 0.007	0.037	0.035	0.036	0.040

TABLE 6  
Freezing-point lowerings of soils kept under optimum moisture conditions and at the temperature of 7°C.

SAMPLE	FREEZING-POINT DEPRESSIONS				
	Original	10 days	20 days	40 days	60 days
	°C.	°C.	°C.	°C.	°C.
1	{ 0.003	0.020	0.014	0.018	0.022
	{ 0.001	0.018	0.018	0.018	0.018
2	{ 0.002	0.014	0.016	0.016	0.020
	{ 0.004	0.015	0.015	0.017	0.020
3	{ 0.002	0.010	0.015	0.012	0.008
	{ 0.003	0.012	0.016	0.015	0.011
4	{ 0.007	0.024	0.027	0.027	0.022
	{ 0.009	0.020	0.026	0.026	0.024
5	{ 0.006	0.015	0.014	0.012	0.006
	{ 0.005	0.014	0.014	0.013	0.008
6	{ 0.004	0.006	0.006	0.012	0.004
	{ 0.005	0.005	0.006	0.010	0.006
7	{ 0.005	0.012	0.014	0.014	0.019
	{ 0.007	0.013	0.013	0.017	0.016

The results of the experiment are shown in tables 5 and 6, and the data for soils 1 and 5 are represented by figures 1 and 2.

It is evident that the accumulation of soluble substances is a relatively slow process under lower moisture conditions. The soils have taken much

*SAMPLE No.1. MT. HOPE*

———— Saturated Moisture - 25°C

----- " " - 7°C.

— · — · — Optimum Moisture - 25°C.

— · — · — " " - 7°C.

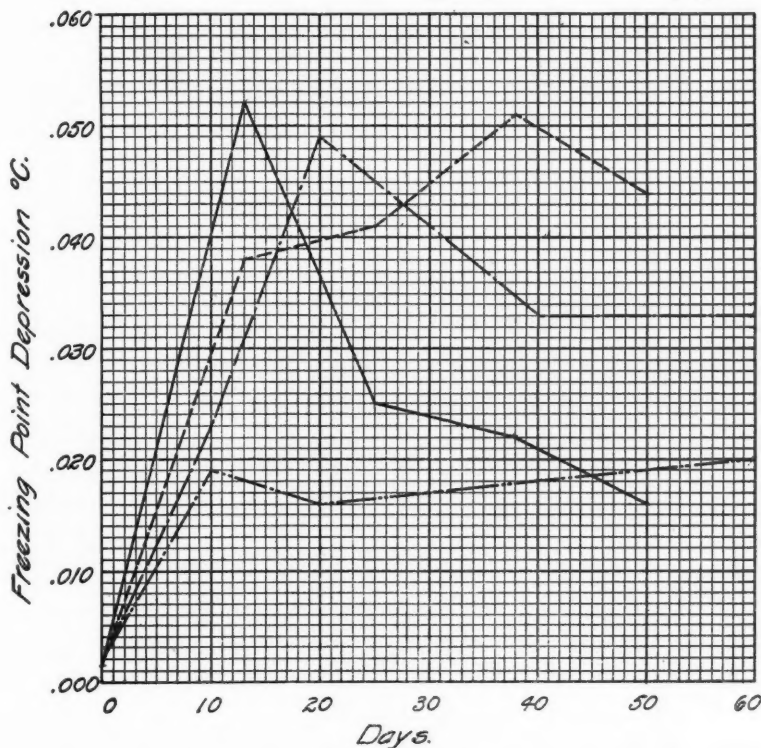


FIG. 1. GRAPH SHOWING THE CHANGES IN CONCENTRATION OF THE SOLUTIONS IN SOIL 1, UPON STANDING UNDER TWO DIFFERENT CONDITIONS OF MOISTURE AND OF TEMPERATURE, FROM THE DATA GIVEN IN TABLES 2, 3, 5 AND 6

longer to reach their highest concentration at optimum moisture than they needed under saturation. In table 5 soils 1 and 6 were highest in 20 days, soils 3, 4 and 5 in 40 days, while no. 2 and 7 were most intense at 60 days. Referring back to the data in table 2, also obtained at 25°C., most of the

samples showed the greatest depression in 13 days. Also, with the exception of soils 1 and 6, larger freezing-point depressions were found in the optimum moisture series, showing that the latter water content produces greater amounts of soluble materials.

*SAMPLE No. 5. CHANDLER*

— Saturated Moisture -25°C.  
 --- " " -7°C.  
 — Optimum Moisture -25°C.  
 --- " " -7°C.

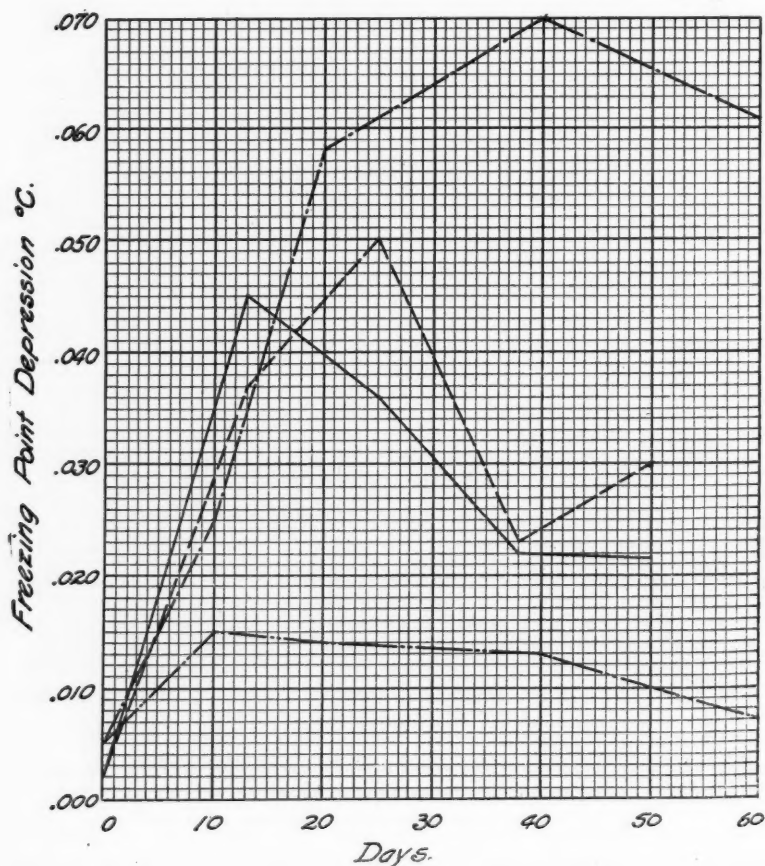


FIG. 2. GRAPH SHOWING THE CHANGES IN CONCENTRATION OF THE SOLUTIONS IN SOIL 5, UPON STANDING UNDER TWO DIFFERENT CONDITIONS OF MOISTURE AND OF TEMPERATURE, FROM THE DATA GIVEN IN TABLES 2, 3, 5 AND 6

As was the case in tables 2 and 3, the lower temperature retards salt formation both in amount and in rapidity. Thus in several soils the maximum readings occur after having stood for 60 days. A very interesting point lies in the comparison of those soils kept at saturated water, and those stored at optimum at 7°C. In all cases, the saturated soils reached a greater concentration than those at the optimum water content. This is in direct contrast to the conditions found in the two series at 25°C. These relations point strongly toward the biological factors, which would find most congenial conditions at a higher temperature with optimum moisture. The facts brought out by the preceding discussions may be stated in general as follows:

At 25°C. the soils produced more soluble material under optimum moisture conditions. Exactly the reverse is true at a temperature of 7°C., at which the saturated soils reached a higher concentration. The higher temperature seems to hasten the rate of formation for all moisture conditions, and saturated moisture increases the rate at both temperatures.

*B. Studies of the relative amounts of soluble material formed by the soil sections of different depths*

The same soils that were used in the preceding work, were sampled at the following depths, care being exercised to eliminate mixing of the various layers. The first sample included the soil from the surface to a depth of 6 inches, the second ranged from 6 to 12 inches, the third from 12 to 24 inches, and the fourth and last from 24 to 36 inches. The depth of 36 inches was always sufficient to reach well into the material which was but slightly, if any, decayed. Referring back to the description of the soils, it will be seen that the lower section in all cases was below the water-table. The samples were permitted to lose water at ordinary room temperature until they attained the optimum moisture content, when they were screened and thoroughly mixed; then 40-gm. portions placed in bottles and stored in a large chamber, the temperature of which remained at 25°C. Determinations of the soluble material present were made at once, and after having stood 10, 30 and 60 days, respectively. As before, care in aerating the bottles was observed during the storage period. The results obtained are set forth in table 7. These freezings were made by adding the amounts of distilled water given in table 4, which brought each sample to a condition of saturation. As in the first experiments the results for two soils, no. 1 and 5, are shown by means of graphs in figures 3 and 4.

The consideration of the data of table 7 resolves itself into two phases: (a) the comparison between different layers of the same soil, and (b) the comparison of the same layer in different soils.

Regarding the first phase, quite uniform tendencies are shown by the data. Thus in all the soils the surface layer gives rise to a greater concentration than any of the lower layers. In all the samples except no. 1 and 7, the second

TABLE 7

*Freezing-point lowerings of soils kept under optimum moisture conditions and at 25°C.*

SAMPLE	DEPTH FROM THE SURFACE	FREEZING-POINT DEPRESSIONS			
		Original	10 days	30 days	60 days
	inches	°C.	°C.	°C.	°C.
1	0-6	(1) 0.012	0.018	0.023	0.032
		(2) 0.010	0.015	0.019	0.034
	6-12	(1) 0.002	0.012	0.015	0.012
		(2) 0.002	0.010	0.015	0.014
	12-24	(1) 0.008	0.018	0.015	0.007
		(2) 0.006	0.016	0.010	0.008
	24-36	(1) 0.010	0.018	0.015	0.012
		(2) 0.008	0.016	0.015	0.010
2	0-6	(1) 0.010	0.017	0.025	0.028
		(2) 0.010	0.014	0.020	0.026
	6-12	(1) 0.012	0.014	0.027	0.026
		(2) 0.010	0.014	0.032	0.022
	12-24	(1) 0.010	0.010	0.020	0.018
		(2) 0.010	0.009	0.017	0.016
	24-36	(1) 0.008	0.009	0.015	0.013
		(2) 0.006	0.006	0.013	0.010
3	0-6	(1) 0.018	0.024	0.025	0.028
		(2) 0.014	0.028	0.029	0.028
	6-12	(1) 0.006	0.002	0.010	0.012
		(2) 0.003	0.005	0.014	0.010
	12-24	(1) 0.006	0.006	0.006	0.011
		(2) 0.004	0.004	0.010	0.008
	24-36	(1) 0.008	0.006	0.008	0.006
		(2) 0.004	0.006	0.010	0.006
4	0-6	(1) 0.010	0.018	0.023	0.024
		(2) 0.012	0.020	0.026	0.025
	6-12	(1) 0.008	0.018	0.020	0.019
		(2) 0.008	0.016	0.021	0.020
	12-24	(1) 0.004	0.009	0.012	0.012
		(2) 0.004	0.012	0.012	0.012
	24-36	(1) 0.004	0.004	0.008	0.006
		(2) 0.003	0.006	0.006	0.005

TABLE 7—Continued

SAMPLE	DEPTH FROM THE SURFACE	FREEZING-POINT DEPRESSIONS			
		Original	10 days	30 days	60 days
	inches	°C.	°C	°C.	°C
5	0-6	(1) 0.018	0.022	0.045	0.042
		(2) 0.016	0.024	0.049	0.038
	6-12	(1) 0.010	0.018	0.040	0.027
		(2) 0.009	0.014	0.040	0.024
	12-24	(1) 0.006	0.010	0.031	0.012
		(2) 0.005	0.009	0.028	0.010
	24-36	(1) 0.006	0.006	0.013	0.007
		(2) 0.004	0.006	0.015	0.004
6	0-6	(1) 0.012	0.018	0.028	0.024
		(2) 0.008	0.014	0.032	0.026
	6-12	(1) 0.008	0.008	0.013	0.006
		(2) 0.006	0.006	0.016	0.004
	12-24	(1) 0.004	0.002	0.008	0.004
		(2) 0.002	0.001	0.008	0.003
	24-36	(1) 0.004	0.002	0.006	0.002
		(2) 0.003	0.005	0.010	0.003
7	0-6	(1) 0.013	0.028	0.048	0.052
		(2) 0.011	0.032	0.052	0.052
	6-12	(1) 0.002	0.028	0.040	0.040
		(2) 0.005	0.026	0.037	0.042
	12-24	(1) 0.010	0.020	0.045	0.037
		(2) 0.006	0.018	0.042	0.034
	24-36	(1) 0.006	0.018	0.020	0.022
		(2) 0.004	0.016	0.020	0.024

layer produces the next highest depression, with the soils below 1 foot in depth, showing but little activity in forming soluble material.

Soil 1 gave consistently higher results in the lowest section over those directly above, the surface being the only portion to outstrip it. This is probably due to the presence of marl just below 3 feet in depth. Sample 7 shows great activity in its third division from the top, which can be explained only by the variation in deposits.

Most deep mucks show a general diminution in the production of soluble substances, under optimum moisture conditions, with increasing depths. This has been found to be true in mineral soils to a large extent. It appears that soil materials which are below the active zone of weathering are more

SAMPLE No.1. MT. HOPE  
 ——— 0-6 inches in depth.  
 - - - - 6-12 " " " "  
 - · - · 12-24 " " " "  
 - - - - 24-36 " " " "

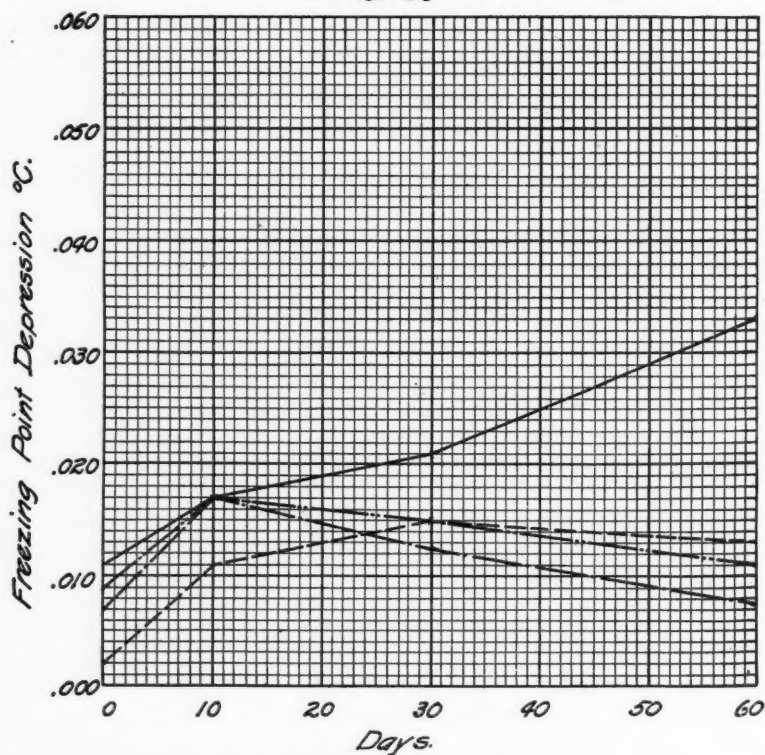


FIG. 3. GRAPH SHOWING THE CHANGES IN CONCENTRATION OF THE SOLUTIONS IN DIFFERENT LAYERS OF SOIL 1, UPON STANDING UNDER OPTIMUM MOISTURE CONDITIONS AND AT A TEMPERATURE OF 25°C.

inert, and would support plant growth with difficulty, if at all. Thus, burning of the surface layers of mucks would probably destroy the most active portions of the soil, and leave the almost inert, unweathered material as the medium for plant growth. Theoretically this might result in crop failure for a few

years until weathering had again made an active layer or one which formed soluble constituents readily. The reasons for the higher solubility of surface layers must lie largely in the realms of biological activity and in chemical decomposition.

*SAMPLE No. 5. CHANDLER*

——— 0-6 inches in depth.

----- 6-12 " " "

— · — · — 12-24 " " "

— · — · — 24-36 " " "

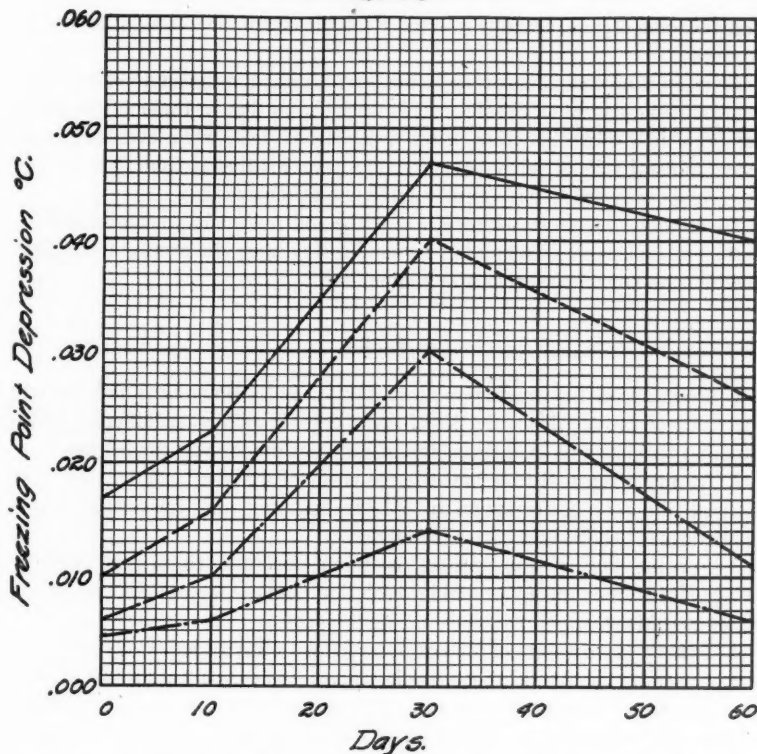


FIG. 4. GRAPH SHOWING THE CHANGES IN CONCENTRATION OF THE SOLUTIONS IN DIFFERENT LAYERS OF SOIL 5, UPON STANDING UNDER OPTIMUM MOISTURE CONDITIONS AND AT A TEMPERATURE OF 25°C.

When a comparison of the same layers in different soils is undertaken, it is found that many of the facts already shown in table 5 are repeated with regard to the surface soils. The order of magnitude of the freezing-point depression for the surface soils is: no. 7, 5, 1, 3, 2, 6 and 4, with the last four

closely grouped. Table 5 shows the highest depressions in soils 7, 5 and 1, as above.

The second layers give results quite similar to those for the surface, being always of somewhat lower magnitude, however.

There are striking similarities in all these soils, in the third and fourth sections, variations of only a few thousandths of a degree Centigrade occurring throughout. For the deposits studied almost regardless of their origin, the material below one foot in depth, shows marked similarities in the amount of soluble constituents. The variation in the relative fertility of muck soils must be caused by the subsequent weathering of this parent mass, which changes some organic remains into more soluble compounds than other debris produces.

An interesting comparison may be made with regard to the depth of weathering of organic and mineral soils. This work shows that in these mucks there has been little climatic action below a depth of 2 feet, while even our most recent mineral soils of fairly heavy texture have weathered from 3 to 6 feet deep, and sandy soils are frequently acted upon even deeper.

There would be a greater zone where the soil materials are more soluble, in mineral soils, and this may have some bearing upon the excessive fertilizer requirements for mineral elements in muck soils.

#### SUMMARY

1. By means of the freezing-point method (used by Bouyoucos and others), the study of the relative activities of seven organic soils under different moisture and temperature conditions, and at different depths was carried out.

2. At any given moisture content, the effect of a higher temperature is to increase the rate of formation of soluble material, and conversely, lower temperatures decrease the rate of formation.

3. For the higher temperatures, optimum moisture conditions tend to bring greater amounts of material into solution than are found under saturated water conditions.

4. Exactly the opposite effect was observed with lower temperatures.

5. Generally moist soils upon standing increase in concentration to a certain point, after which a decline occurs. This is probably due to the following causes: (a) reabsorption, (b) chemical change to less soluble compounds, or (c) biological activity.

6. Organic soils vary at different depths in the amount of soluble substances present.

7. Different depths also vary in the rate and amount of material made soluble upon standing.

8. Below a depth of 2 feet, the muck soils studied are very inactive.

9. The surface layers usually produce the bulk of the soluble plant-foods.

10. In general the ability to yield soluble materials decreases regularly from the surface to the water-table.

11. The zone of weathering and the region of greatest activity closely coincide.

#### REFERENCES

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- (2) MCCOOL, M. M., AND MILLAR, C. E. 1918 Soluble salt content of soils and some factors affecting it. Mich. Agr. Exp. Sta. Tech. Bul. 43.